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Bachelor Thesis

"Voltage control in Smart Grids"

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ABSTRACT

Smart grids are slowly becoming a reality, and will soon become embedded in all aspects of society: legislation, economy, environment, etc. Voltage control and reactive power compensation are crucial for the smart grid development. This project provides a background on all these issues and focuses on determining which the best device to control voltage is. The study was carried out on the IEEE 34 Node Test Feeder using the Power Factory DIgSILENT software. It was found that StatVars, dynamic devices, keep voltage more stable and within regulated limits than capacitors, and that nodes at the end of lines or acting as sole connection for more than two segments of network, and therefore under high loading stress, are more vulnerable to voltage drops. Therfore, meshed network topologies are more favourable for stable voltage and smart grid development. Using this knowledge, smart grids will be developed. This will enable a higher penetration of renewable energies and therefore a reduction of greenhouse gas emissions, a more competitive electricity market and an overall improvement of society's state of wellbeing.

Keywords: Voltage control, Reactive power compensation, DIgSILENT, Smart Grid, Transition

RESUMEN

Las redes inteligentes se están transformando poco a poco en una realidad, y pronto estarán integradas en todos los aspectos de la sociedad: legislación, economía, medio ambiente, etc. El control de tensión y la compensación de potencia reactiva son cruciales para el desarrollo de la red inteligente. Este proyecto proporciona una base sobre todas estas cuestiones y se centra en determinar cuál es el mejor dispositivo para controlar la tensión. El estudio ha sido llevado a cabo sobre la red de prueba IEEE 34 usando el programa de DIgSILENT, Power Factory. Se encontró que los StatVars, dispositivos dinámicos, mantienen la tensión más estable y dentro de los límites regulados que los condensadores, y que los nodos al final de líneas o que actúan como única conexión de más de dos segmentos de la red, y por tanto bajo un alto estrés de carga, son más vulnerables a caídas de tensión. Por lo tanto, las topologías malladas son más favorables para una tensión estable y el desarrollo de la red inteligente. Usando este conocimiento, las redes inteligentes podrán desarrollarse. Esto permitirá una penetración más alta de energías renovables y por tanto una reducción de las emisiones de gases de efecto invernadero, un mercado eléctrico más competitivo y una mejora global en el estado de bienestar de la sociedad.

Palabras clave: Control de tensión, Compensación de potencia reactiva, DIgSILENT, Red Inteligente, Transición

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1. INTRODUCTION

1.1. Importance and necessity of voltage control in distribution networks

Voltage control understood as keeping its magnitude and frequency within determined ranges and having a smooth curve with low harmonics is vital to the operation of the electrical grid, especially in distribution networks [1]. Controlling the voltage ensures that the consumers can operate their electric devices correctly and without damage and that the network is kept stable and without faults that can rapidly evolve into blackouts.

This is becoming more and more critically important with the spread of distributed generation and smart grid transition [2]. Unpredictable renewable generation, demand management and other aspects of smart grids require a dynamic operation of the grid in order to keep it stable, and devices that can react automatically to variations in the electrical current are essential.

It is important to note that voltage control will not only help the transition to smart grid in developed countries, but also the construction of a resilient and reliable smart grid in developing countries, which would allow them to grow sustainably and fairly. Significant progress has been made in China, India and Brazil [2].

1.2. Objectives and reach

The present project's main objective is to study the behaviour of a radial distribution network in different scenarios in order to determine which reactive power control device is more effective for keeping voltage levels within acceptable ranges and thus facilitate the transition to a smart grid. This comprises several tasks.

First it was necessary to know what distribution networks are, how are they classified and which are their main components. Then, the smart grid concept was defined, and its problems studied to narrow the aim of the study.

The aim is specifically about voltage stability and comparing the effectiveness of different devices to achieve it, so it was necessary to analyze voltage stability and the methods and devices necessary to achieve it.

Since the means by which the study is going to be performed are the IEEE-34 Node Test Feeder and DIgSILENT Power Factory 2017 software, both were studied, their structure, functionalities, etc.

An active learning process and reinforcement of the previously described concepts was developed through the simulations performed for the study and analysis of the results they produced. Overall, 115 simulations were performed on the network:

- Unbalanced network
  - Load flow
    - Simple
    - With StatVars
    - With Capacitors
  - 24 hour load scenarios
    - Load flows with StatVars
    - Load flows with Capacitors
  - 24 hour load and generation scenarios
    - Load flows with StatVars
    - Load flows with Capacitors
- Balanced network
  - Load flow
    - Simple
    - With StatVars
    - With Capacitors
  - Sensitivity analysis
    - Simple
    - With StatVars
    - With Capacitors
  - 5 weakest nodes
    - QV curves
    - PV curves

Finally, an analysis of the economic and social dimension of voltage control and smart grids is done to put the project in a broader context and better understand its importance.

1.3. Structure of the report

In order to facilitate the understanding of the present project a brief summary of its parts is provided below.

In the first and present chapter, an introduction of the voltage stability issue in relation to smart grids and the path followed to study it in the present project is given.

The second chapter delves in the concept of distribution network: what is it composed of, what is voltage stability in its context and by which norms is said stability regulated.

The third chapter provides an insight in the functionalities and tools of the software DIgSILENT Power Factory.

The fourth chapter details the process followed to model the IEEE-34 Node Test Feeder, from the processing of the data provided by IEEE to their implementation in the software.

The fifth chapter describes the simulation process while it presents and analyzes the results from the simulations detailed in section 1.2.

The sixth chapter studies the economical dimension of the reactive power compensation devices simulated in chapter 5 and estimates the cost of this study.

The seventh chapter reviews the social importance of a stable and reliable electricity supply and smart grids.

The eighth and final chapter wraps up the project and provides a conclusion.

2. DISTRIBUTION NETWORKS: SMART GRIDS

2.1. Introduction

The electric grid is formed by the subsystems: generation, transmission, distribution and utilization. They are separated by their voltage level, and connected through transformers and substations. Transmission is done in high voltage (HV), above 33 kV, and utilization in low voltage (LV), around 0,4 kV.

Medium voltage (MV) ranges in between them, although these levels vary significantly between countries. MV is comprised of most distribution networks, and also is where distributed generation and large industrial consumers are connected [3]. This is a particularly sensitive level of the electrical network. It is low enough that voltage variations have a noticeable impact on it, but also high enough that part of it will need to be tripped off in case a fault happens to avoid it spreading [4].

Distribution networks can be classified according to their topology. Urban distribution networks are meshed, with high interconnection and load levels. This topology is more expensive, but also more reliable as it has redundant elements [3]. They usually have their lines buried for safety. On the other side of the spectrum are rural networks, with a much lighter load profile and long lines arranged in a radial pattern. Radial topology is cheaper, but customers are more vulnerable to being switched off in case of fault. It usually has aerial lines due to the expense of burying kilometers of lines, but voltage drops are higher than in subterranean lines due to their lower diameter [3].

Besides distributing electricity, distribution networks must also keep it stable and within established limits. This is done through reactive compensation devices, but also through the tap changers of transformers in substations. They are equipped with automatic changing in the higher voltage side and manual changing in the lower one to compensate for voltage deviations [3].

What differentiates smart grids from regular distribution networks is their capacity to operate these devices dynamically and safely thanks to an update in transmission infrastructure and implementation of telecommunications technologies. Amin's definition focuses on the technological aspects [5]:

> *"A self-healing grid uses digital components and real-time communications technologies installed throughout a grid to monitor the grid's electrical characteristics at all times and constantly tune itself so that it operates at an optimum state."*

Smart grids are also referred to as "self-healing" due to their capacity of not only monitoring the grid and anticipating faults, but also isolating them from the rest of the network and rerouting electricity transmission [5].

This capacity of smart grids in turn allows wider improvements in the overall network: integration of stochastic and distributed generation, energy storage, plug-in vehicles management and even demand response. It will, and currently is in Spain with the state implementation of smart meters, allow to know precise electricity consumption patterns and charge for electricity accordingly, improving market competition and levelling off the demand curve, or prioritize supply to critical services or infrastructures in case of fault.

However, the transition to smart grids is happening slowly and locally. Years of debating over the role of private and public entities, lack of leadership and general uncertainty have left electrical infrastructures and regulatory framework outdated, which are essential to the success of the smart grid [5]. This change requires not only constant monitoring, but also a change in the structure of the electrical grid to one of microgrids connected to the transmission grid acting as a backbone, as well as the implementation of devices capable of controlling faults, managing the integration of the technologies described above and keeping voltage to adequate levels.

2.2. Control and voltage stability

As explained in section 1.1, stability in distribution networks is one of their key aspects, and therefore the analysis of said stability and the methods to achieve it are key as well.

The network in normal operation is subject to variations in load and generation due to connection, disconnection and variation in the levels of large generators or industrial loads. The analysis of the network must mimic these variations, simulating the system in different static and dynamic scenarios, including faults. The main parameters evaluated during the analysis are rotor angle, voltage frequency and voltage magnitude.

Rotor angle stability relates to the capacity of the synchronous machines connected to the grid to keep their synchronism in normal conditions and regain it in presence of faults. It depends both on the initial state of the system and the clearing time of the fault [6].

Frequency stability is associated to the balance between generation and demand. If generation is higher than demand frequency will go up, as there is less opposition to the inertia of the generators, and vice versa. Frequency stability disturbances need to be cleared very quickly to avoid it being spread, and this is usually done by means of the synchronous generators, that can react instantaneously [6].

Voltage stability ensures that voltage levels at each node in the system are kept within the values defined by the applicable norms, described in section 2.3 for our case. Voltage magnitude is related to reactive power flow, which makes nodes farthest from generation sources more vulnerable to drops [6]. This is the parameter that will be studied in the present report.

Some voltage stability analysis techniques are [7]:

- Direct method: uses power flow equations and singular conditions. It requires high computational capacity and good initial conditions.
- Modal analysis method: decomposes the Jacobian matrix of power flow to reveal information about the weakest areas in the system.
- Continuation Power Flow method: computes successive power flows and traces the PV curve iteratively.
- Optimization method: is similar to the direct method but allows introducing more variables such as voltage and temperature constraints.

2.3. Voltage control regulation in distribution networks

Voltage control is regulated by both national and international norms, which is not surprising considering its importance, described in section 1.1. Ensuring quality and continuity of supply is key during construction and operation of the network.

In the case of Spain, the norm regulating voltage parameters is the RD 1955/2000, which is subject to the European norm UNE-EN 50160. These norms include the admissible values for voltage magnitude and frequency, described in table 2.1, and limitations for overvoltages, voltage gaps, harmonics, instabilities, etc.

In particular, RD 1955/2000 defines quality of service as continuity and quality of supply and quality of consumer service, and also the different requirements of continuity depending on the urbanization of the area [8].

<table>
<tr><th rowspan="2"></th><th rowspan="2">UNE-EN 50160</th><th colspan="2">RD 1955/2000</th></tr>
<tr><th>LV</th><th>MV</th></tr>
<tr><td>Voltage</td><td>±10% for 95% of time</td><td>±7%</td><td rowspan="2">80% of described tolerances</td></tr>
<tr><td>Frequency</td><td colspan="2">±1% for 99.5% of time
-6%/+4% for 100% of time</td></tr>
</table>

Table 2.1. Voltage tolerances according to Spanish and European norms [8], [9]

The smart grid will require new regulations as its operation differs from that of traditional grids and the amount of information retrieved in order to make it work will need appropriate protection. Steps have been taken in this direction with the norm IEEE P2030 [10], which focuses on the interoperability of the several systems that compose the smart grid, as well as many local initiatives in the form of roadmaps rather than actual legislation. Many of the present efforts are devoted to pilot projects, but, as explained in section 2.1, real, integrated smart grids still belong to the future.

A recent aspect of regulation that is promising for voltage control and smart grids is the Network Codes [11]:

> *"Network codes are a set of rules drafted by ENTSO-E, with guidance from the Agency for the Cooperation of Energy Regulators (ACER), to facilitate the harmonization, integration and efficiency of the European electricity market."*

ENTSO stands for "European Network of Transmission System Operators". They were brought together to define network codes that could appropriately manage the new technical, environmental, social and economical challenges the EU faces [11]. These codes focus on markets and connection aspects and are of direct application in all member states. They, however, need to be integrated in each state's national regulation, so they will be effective in 2019 after a three year adaptation period [12].

Market Network Codes deal with daily and intra-day markets, long term markets and cross-border connection markets [12].

Connection Network Codes deal with electricity generation, demand and HVDC connections. They are extensive documents that specify, as a function of the type of installation and the region: the time the installation has to resist frequency fluctuations or voltage gaps, active and reactive power generation requirements, how compliance tests are to be carried out and delivered, exemption procedures, responsibility assignment, etc [12].

2.4. Distributed generation in distribution networks

It can be tempting to define distributed generation simply as "small scale electricity generation", but there is more to it. Many definitions have been given, with the focus on factors such as generation capacity and technology, not being controlled centrally or being consumed within the same distribution network [13].

Distributed generation was the norm in the beginning of electrical networks due to their limited transport capabilities. After the appearance of AC networks that allowed electricity transport throughout long distances it was relegated to a secondary role. Recently the interest in distributed generation has resurfaced due to two main factors: electricity market liberalization and environmental concerns. Distributed generation can help keep both power prices and power supply stable and decrease the need of grid expansion and use by generating on site [13].

However, distribution systems are not designed to have any generation in them or at their loads, and introducing distributed generation can impact the power and voltage conditions in the system. Since networks are made to withstand undervoltages during high load coincidence, having distributed generation may lead to overvoltages [3]. Many variables should be considered to determine this, such as size and location of generation, regulator and transformer settings and impedance characteristics of the line.

Some impacts may be positive. These include improved power supply, loss reduction, transport capacity release, reactive power compensation through inverters, etc. These positive impacts are more difficult to achieve than it seems, as they require suitable coordination, control and strategic placement. An excess of distributed generation can cause major economical, technical and environmental issues if not handled appropriately, mainly due to efficiency [13], [14].

The same amount of power is produced less efficiently by many small units than by a single large one, which in turn affects cost. Environmentally, distributed generation is only an advantage in the case of renewable energies, like wind, photovoltaic solar or small and micro turbines. Non-renewable based distributed generation are fuel cells, Stirling engines or internal combustion engines, and the reduced production efficiency described above increases greenhouse gas emissions in their cases [13], [14].

One of the main technical challenges is reverse or bidirectional flow. Reverse flow happens when distributed generation is higher than local demand, but only for active power, while Q still increases due to the inverters' requirements [3]. For distributed generation to manage Q it would need to limit P, which their owners do not want to do so it is not a useful method [4]. Besides, it is hard to manage, as the system operator needs to monitor many sites, which is usually not possible because distributed generation is privately owned [13], [14].

2.5. Reactive power compensation systems

The main reactive power compensation devices used in the industry are capacitor banks, SVCs and STATCOMs. However, more important than the devices themselves is their operation. Traditionally, they have been managed by tap changing transformers and regulators [14] , but these fall short before the complexity of the problem. As such, new algorithms are being developed to tackle this issue [1], [15].

2.5.1. Traditional control

The main elements that have to be taken into account for voltage and reactive power control in networks are generators, lines and transformers [4].

Synchronous generators can either generate or absorb reactive power, as well as PV with its inverters, but asynchronous generators, used mainly in wind energy, only consume reactive power [4].

Reactive power generated by a line depends quadratically on voltage, if it is consumed, on current. Reactive power is usually consumed during the day, when current levels are high, and generate it or have a capacitive behaviour, known as Ferranti effect [16], during the night. Consequently, lines can only be used to reduce voltage levels in transport networks, especially in highly loaded lines [4].

Transformers and voltage regulators, similar to autotransformers, can intervene thanks to their variable tap. The effect of stepping up voltage is capacitive, of stepping down, inductive [4].

2.5.2. Capacitor bank

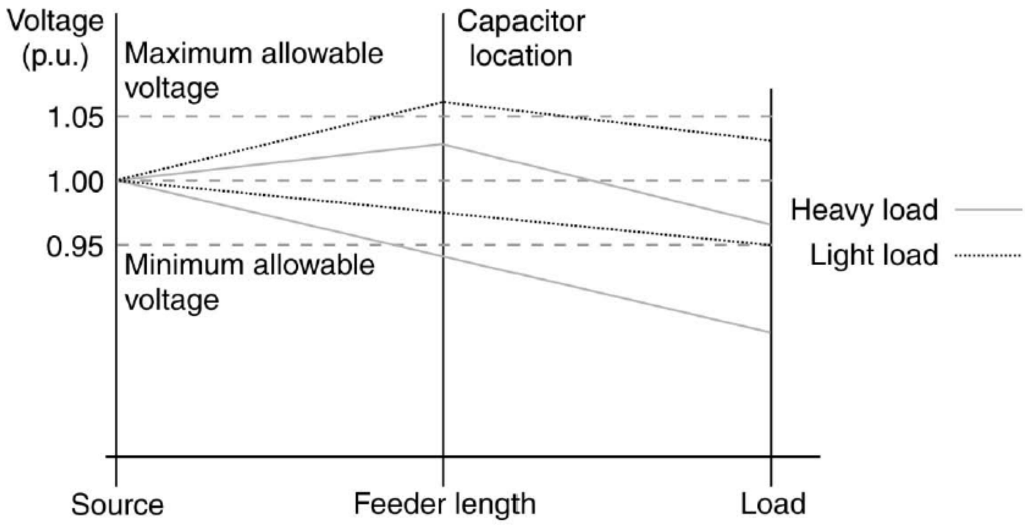

Figure 2.1. Voltage under heavy and light load with a capacitor [17]

Shunt capacitors are the most used control device in power distribution systems, despite their non-dynamic operation. The main technical factors taken into account when choosing between capacitors and other devices, or among capacitors, are the distribution factor, the total loads, and the voltage and power factor at those loads.

Capacitors' functions include voltage and reactive power regulation. While an adequately selected and placed shunt capacitor will keep voltage within acceptable limits during heavy load, at light load the voltage will be increased above those limits. To avoid this, switched capacitor banks are used, so that they are switched out when the load is light and they are not necessary [17] This behaviour is described in figure 2.1.

They compensate inductive current by adding capacitive current, thus reducing the total current flowing, voltage drop and losses by reactive power. Some of the effects of a sustained low power factor (highly inductive current) are overheating, higher losses and permanent damage because of high currents, low voltage, higher electricity consumption and investment in facilities to obtain the required active power.

2.5.3. Static compensators of reactive power (SVC/StatVar)

A Static VAr Compensator, or SVC, also known as StatVar, is a combination of the following components, schematized in figure 2.2:

- Thyristor controlled shunt reactance (TCR) (units)
- Shunt capacitor banks (steps)
  - Thyristor switched capacitor (TSC)
  - Mechanically switched capacitor (MSC)

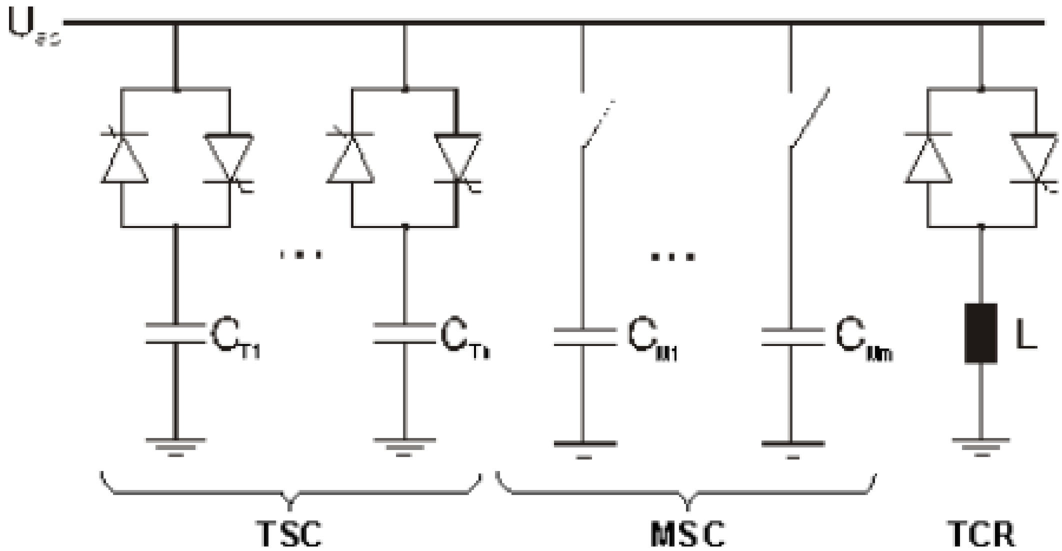

Figure 2.2. StatVar schematic [18]

A StatVar can control voltage at the busbar to which it is connected, or at a remote one. Its effect is similar to that of a capacitor bank, but it can be operated dynamically. Capacitors are switched on and off automatically in response to changes in reactive power demands. The thyristor controlled shunt reactance continuously controls the frequency of the current through the device, harmonizing the power delivered [17].

2.5.4. FACTS and StatCom

Flexible AC Transmission Systems are highly interconnected networks that minimize the need for large power plants. FACTS devices can achieve voltage control standards and an operating flexibility [7] that are out of range for mechanically switched devices, and will continue to expand as the electrical industry becomes more competitive [19].

A Static synchronous Compensator or StatCom is one of these FACTS devices, used typically for voltage support. It is shunt connected to the grid and can generate three phase sinusoidal voltages, with rapidly controllable amplitude and phase angle. The most common topology uses GTO thyristors and inverters in multiple steps, which avoid harmonics. It is connected to the grid by a multi-winding transformer on one side, and to a capacitor to the other [19].

Rao [19] found that it is better to use StatComs in combination with capacitor banks. Capacitor banks alone may exacerbate low voltage levels, and StatComs placed in close proximity may cause coupling issues.

2.5.5. Algorithms

The operation of tap changers and reactive power compensation devices must optimize power losses, cost and voltage profile. Conventional non linear programming techniques fail to solve the complexity of this problem, as they do not consider the global effects on the network. To do this, human knowledge, experience and judgement is required, and for it, a myriad of artificial intelligence methods have been studied since mid XX century [1], [15].

Some of them are Expert Systems, easily managed but unable to adapt, Artificial Neural Networks, fast and robust but hard to use, Fuzzy Logic Programming, Tabu Search and various hybridized versions. However, the most popular and widespread by far are the Evolutionary Computing Algorithms, specifically, its subdivision Genetic Algorithm, which accounts for 95% of published papers on power systems [1], [15].

ECA is based on Darwin's evolution theory: only the fittest survive and reproduce. ECA runs several randomly generated solutions, iterates them with methods from population genetics, and selects them in terms of how fast and accurate they solved the task. GA uses coding and cross-reproduction to find the best solution. It does not require precise information on the objective function, but that implies it requires a large amount of computation time [15].

Because of that, Dong Guan [1] proposes a variation called Micro-GA. It starts with a very small population and uses a low mutation rate. This allows the algorithm to converge in few iterations. To achieve the best solution possible, Micro-GA is run in succession, retaining the best solution from the former one. The algorithm is described in figure 2.3.

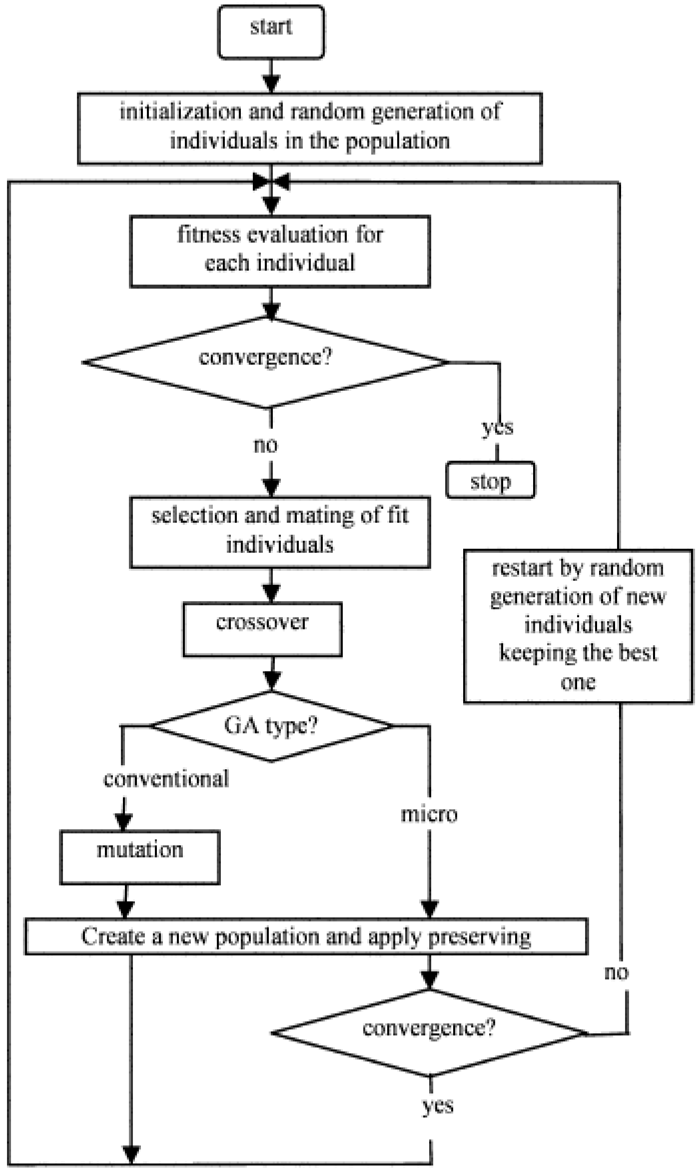

Figure 2.3. Micro Genetic Algorithm Flow [1]

3. VOLTAGE CONTROL WITH DIGSILENT POWER FACTORY

3.1. Power Factory 2017

Figure 3.1. DIgSILENT logo [20]

DIgSILENT Power Factory (figure 3.1) is an engineering software for the analysis of transport and distribution electrical networks, as well as industrial power systems. It is an interactive, advanced tool, capable of designing, simulating and analyzing power systems in order to understand their behaviour in a wide range of scenarios and optimizing them accordingly [20].

This software allows the user to define and simulate different study cases within the same project, which, together with intuitive graphic tools and standardized component libraries, allows the user to develop their projects efficiently. Power Factory is also flexible by allowing to import and export data to and from a variety of platforms, such as Microsoft Excel and PSS/E, and to write code in DPL (DIgSILENT Programming Language) to avoid performing simulations and extracting results manually [18].

The version of Power Factory used in this project is PF4T, or Power Factory For Thesis, which is free but has limited functionalities. It allows to perform load flows, and sensitivity analyses and PV and QV on balanced networks only. This meant the voltage profile optimization and optimal capacitor placement, as well as any dynamic analysis were out of range. An extension of the license was requested to allow more than the original 50 nodes limit.

3.1.1. General design

Power Factory is designed to be used mainly through its graphic interface (figure 3.2). The user introduces different elements from the software's libraries and connects them manually. Then, the elements are assigned their parameters by double clicking on each of them and introducing the required values.

Besides the graphic interface and a basic toolbox, Power Factory's main page also includes an output box that informs of the progress of the simulation, as well as any problems that may arise in specific elements.

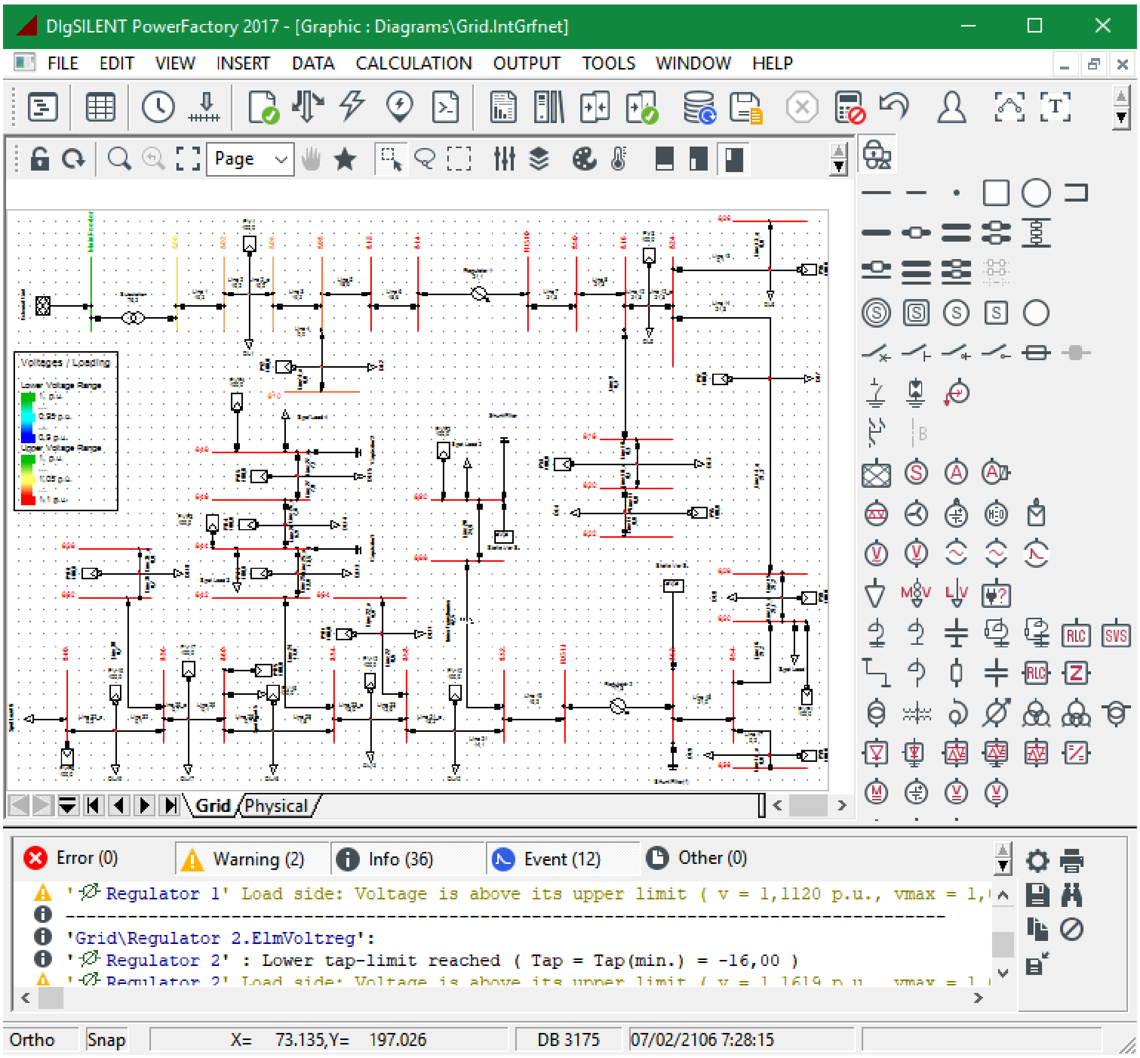

Figure 3.2. Power Factory graphic interface

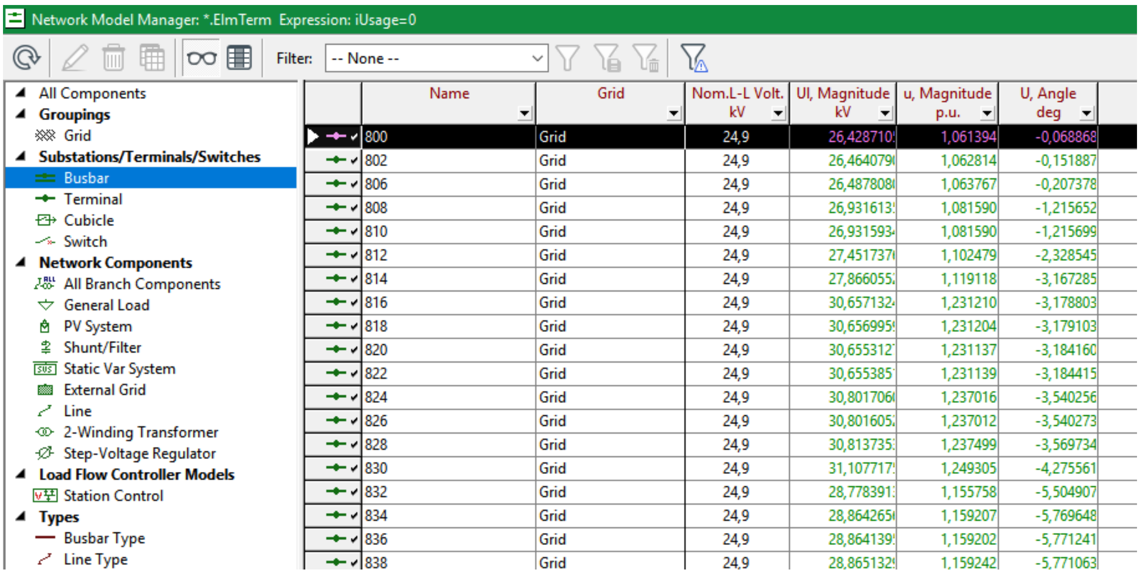

Figure 3.3. Power Factory Data Manager

Parameters can also be accessed through the Data Manager (figure 3.3), which groups elements by types: lines, loads, etc. This is especially useful when updating a specific parameter or when exporting to Microsoft Excel an array of data of all the elements within a category. After a load flow simulation, the Data Manager also holds the resulting parameters, which can be selected (figure 3.4), for each element.

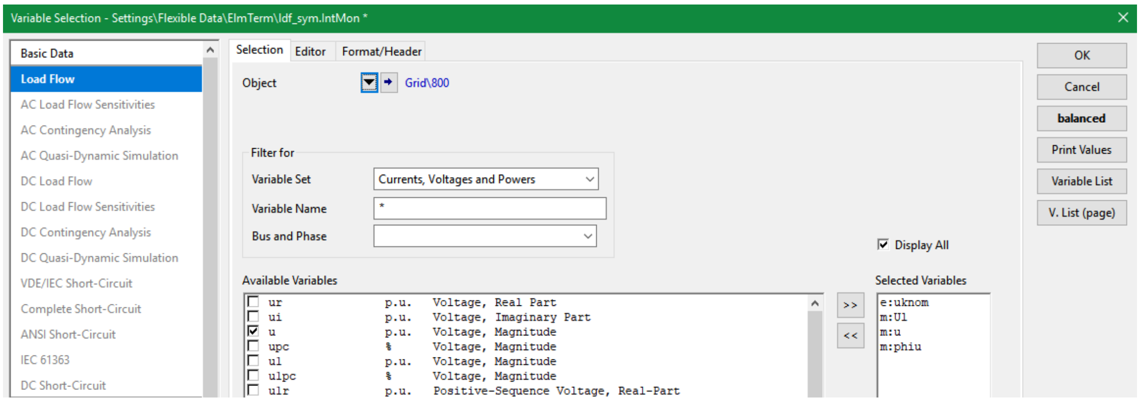

Figure 3.4. Output variables selection for the Data Manager

One of the most important characteristics of Power Factory is the feature of Case Studies. These are different operation scenarios that can include variations in certain parameters or adding or eliminating components. Operation scenarios can be load and generation wise, like in section 5.3, but also predictions of how the network will evolve.

3.1.2. Help tools

This software provides the user with wide and detailed support material on the use of the software and mathematical descriptions of the element models with clarifying examples. This material includes:

- Frequently Asqued Questions forum [21]
- Beginner tutorial
- General user manual
- Technical reference for each element
- Scripting references

3.2. Load flow

The load flow is essential when analyzing an electric network.

A load flow calculates the voltage levels in all the nodes of the system, as well as the loading levels of elements such as lines and transformers. These in turn allow to deduce where losses happen, what parts are congested, and therefore where it is optimal to connect auxiliary devices to stabilize it.

Load flows are performed in stationary state, that is, with all its variables constant and without any short-circuit events defined.

3.2.1. Inputs

The basic choices the user can make when performing a load flow are, as shown in figure 3.5, regarding the calculation method, voltage, active and reactive power regulation, temperature dependency of lines and cables and load options. Only these were used:

- The calculation method was initially unbalanced due to the unsymmetrical nature of the feeder, and was changed to balanced in order to perform the calculations for section 5.5.
- Automatic tap adjustment of phase shifters and transformers was chosen to control power and voltage.
- Considering voltage dependency of loads was important to model them as constant impedance, current or power.

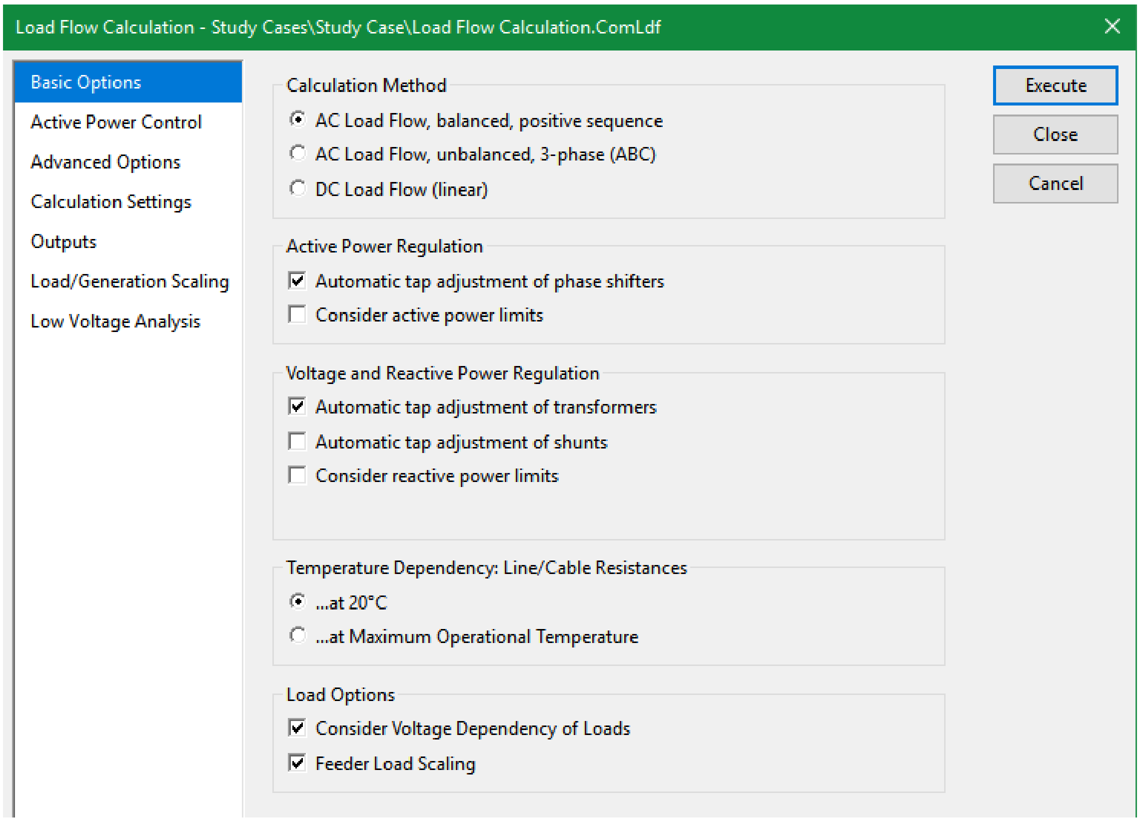

Figure 3.5. Basic Options for the Load Flow Calculation

The calculation settings, in figure 3.6, allow the user to specify the method used to compute the iterations and the number of them, as well as the desired precision of the results. This allows the user to trade off between accuracy and simulation time.

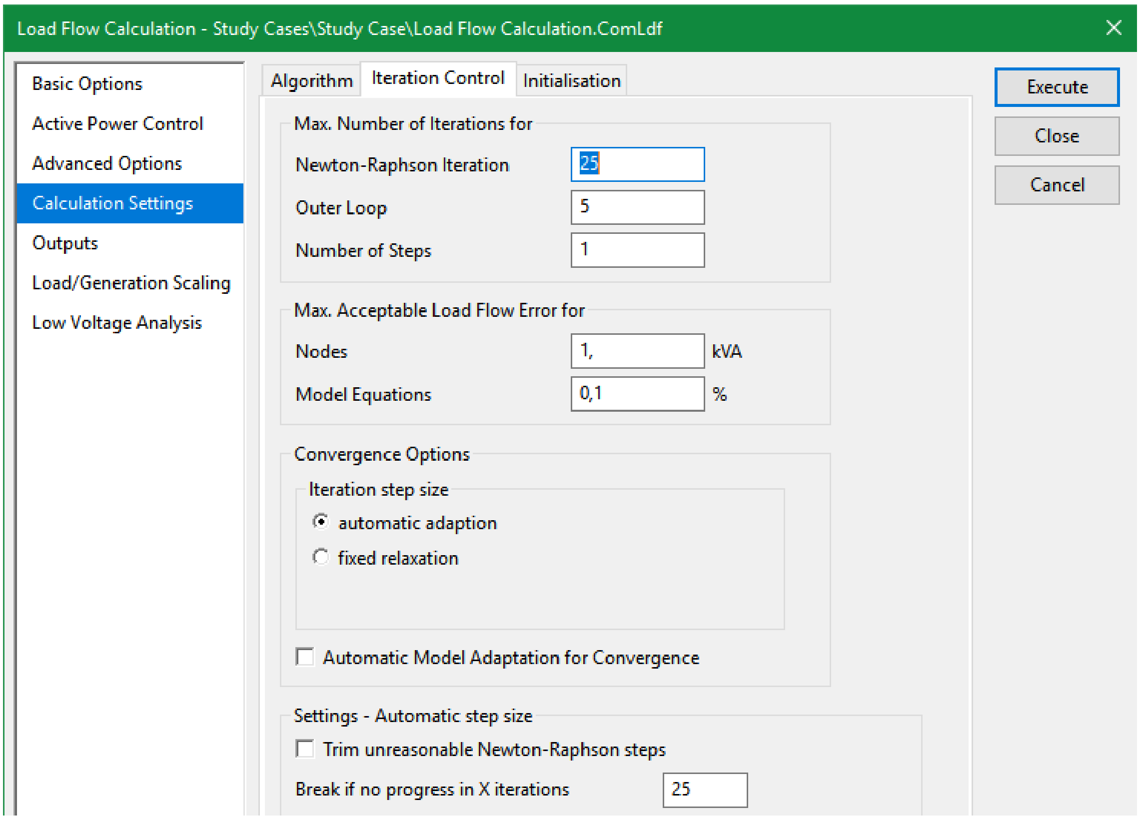

Figure 3.6. Calculation Settings for the Load Flow Calculation

3.2.2. Outputs

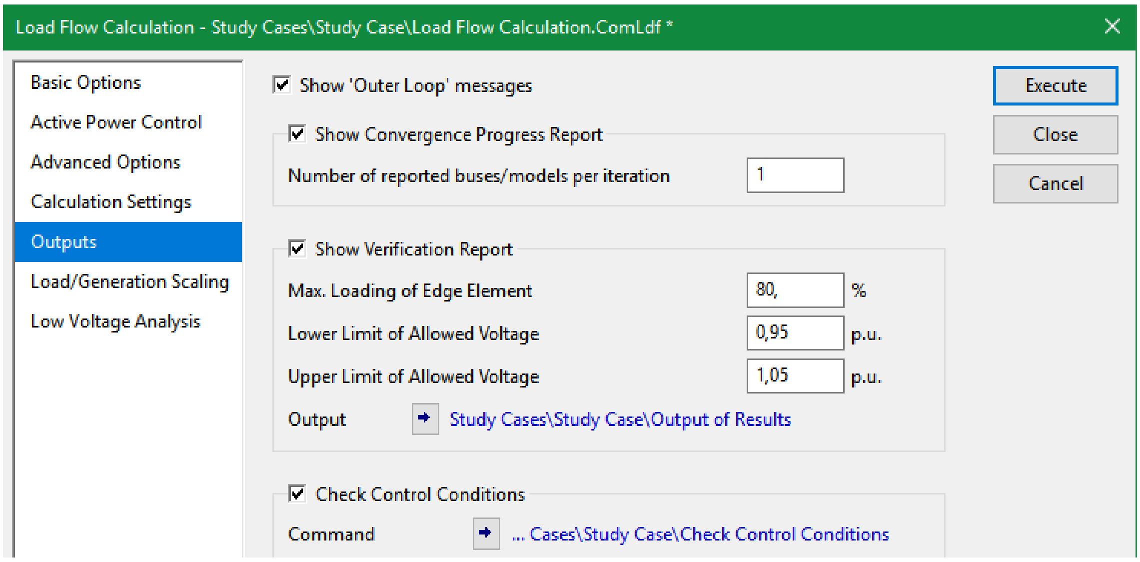

Figure 3.7. Outputs for the Load Flow Calculation

The output options (figure 3.7) define the detail of the report on the progress of the simulation. Selecting these options helps detect problems within the network or convergence.

3.2.3. Visual aids

Power Factory also includes colour options that can help visualize better the issues within the network. Said colours can be defined as shown in figure 3.8. It allows to show the different voltage levels in a network before a load flow. After a load flow it can show the loading of elements and voltage magnitude and angle.

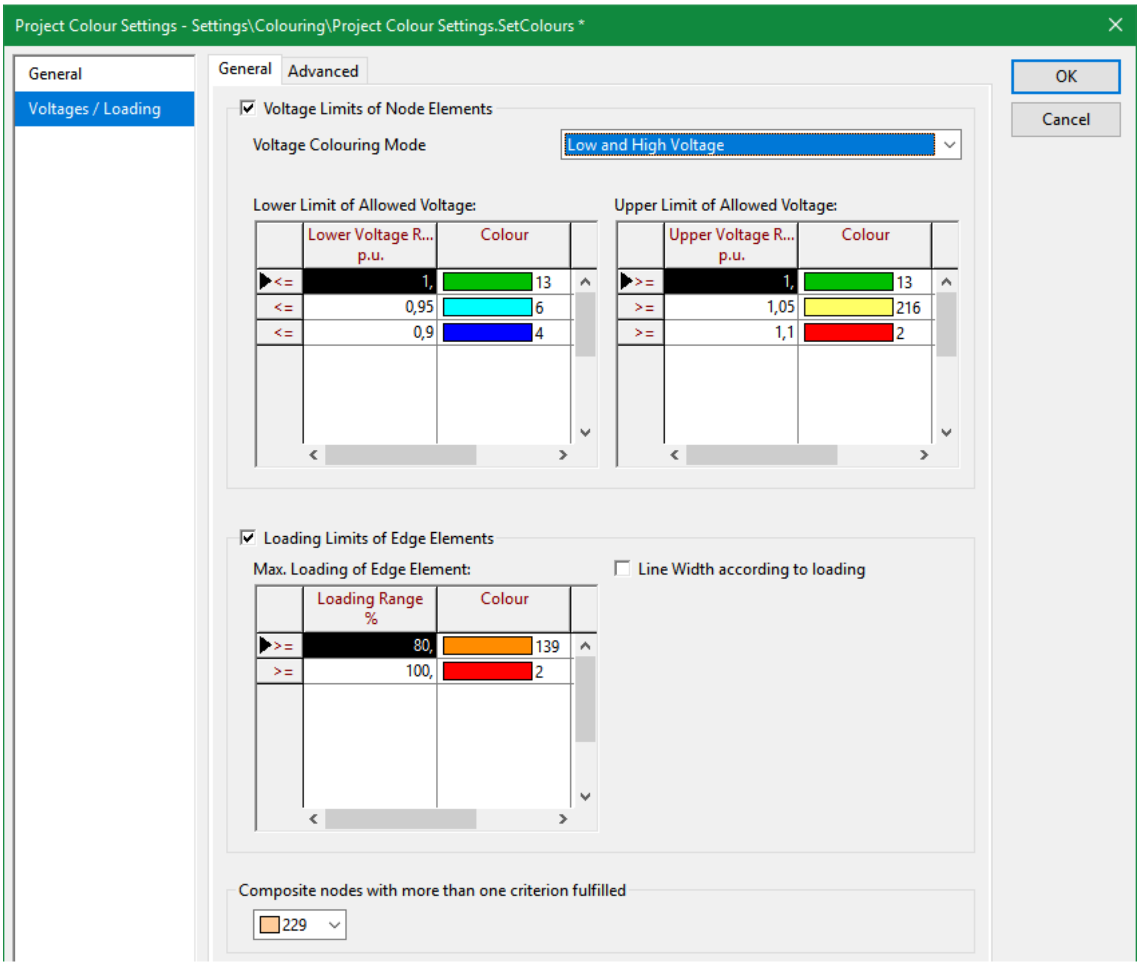

Figure 3.8. Colour Settings

3.3. Voltage stability

The voltage stability tools provided in the PF4T license were only the "Transmission Network Tools", which consist of QV and PV curve calculation and plotting. The user just needs to select the buses they want to study and the size of the curve step for precision. The output consists of bus voltage at a series of steps of reactive and active power, respectively. This output can be exported to *.csv format, compatible with Microsoft Excel.

4. MODELLING

4.1. IEEE-34: The chosen network

The chosen network to model is the standard IEEE-34, as shown in figure 4.1, one of the five benchmark distribution feeders published by the IEEE Power Engineering Society Distribution Subcommittee. Node test feeders are defined by having a single path for power to flow from the source to the loads.

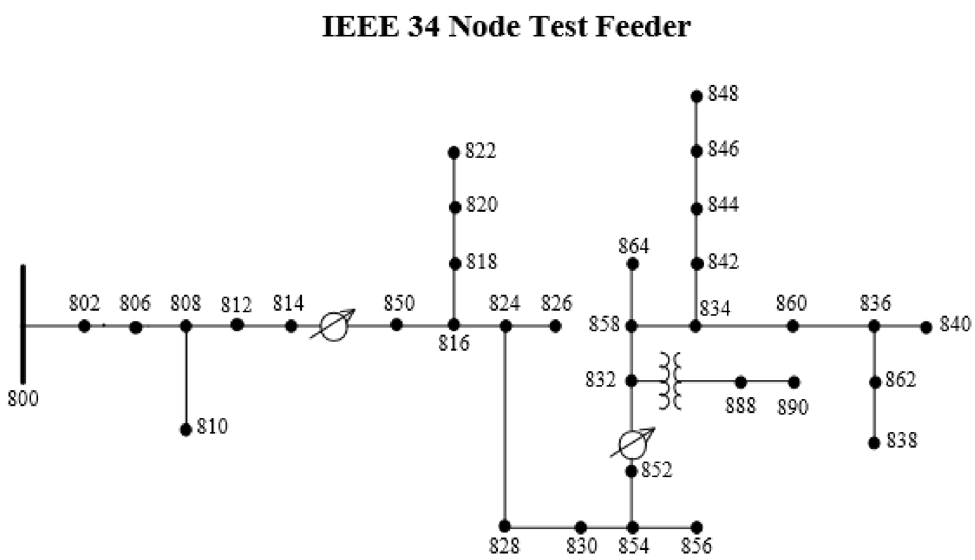

Figure 4.1. Feeder schematic [22]

This node test feeder is an actual feeder located in Arizona, USA, with a nominal voltage of 24,9 kV and eight ramifications or branches. The external grid is of 69 kV, and one of the branches is of 4,16 kV. The three sections are connected with two winding transformers. There are also 2 in-line step voltage regulators, 2 shunt capacitors, 6 spot loads and 19 distributed loads.

It is characterized by being long and lightly but unevenly loaded, which makes it conflictive to model and provokes convergence problems. This feeder was modelled with the orientation of Adewole's [23] thesis and the standard data provided by the IEEE [22]. Said data are detailed in Annex A.

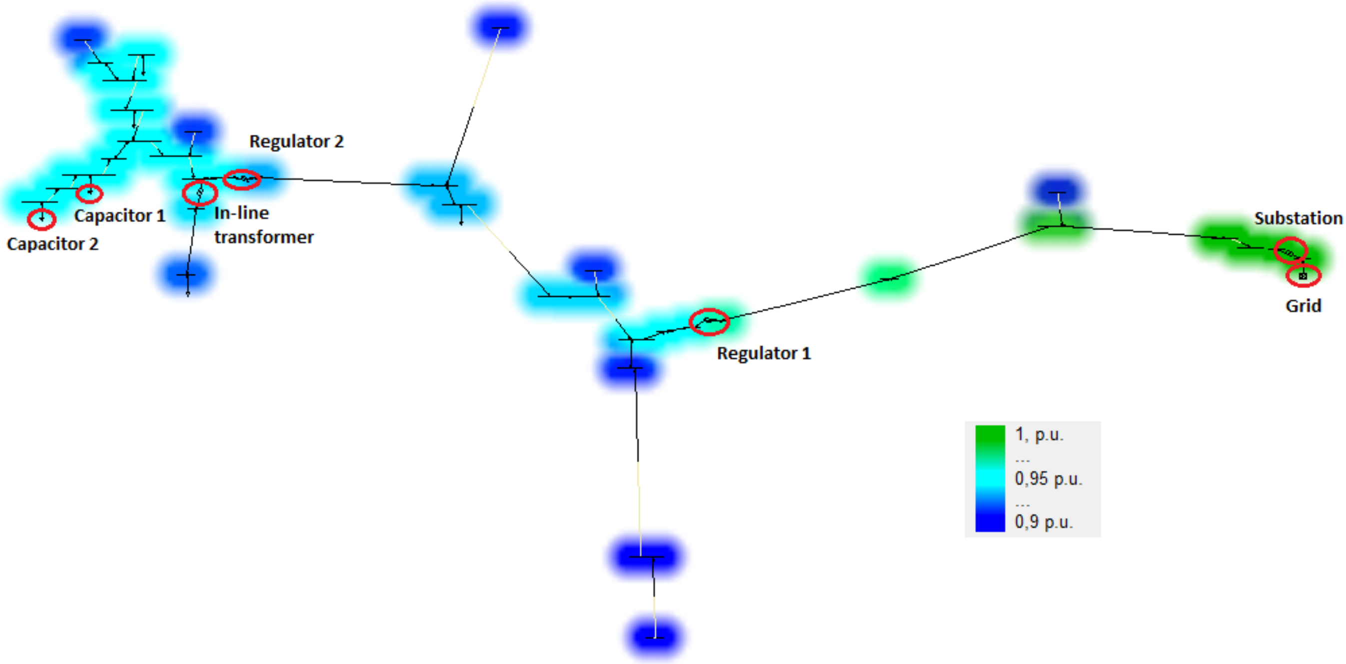

Figure 4.2. Physical approximation of the feeder and heatmap

The heatmap (figure 4.2) provides an overall idea of the situation of the voltage levels in the feeder. The buses in some secondary branches appear in dark blue because the heatmap generator does not recognize them being single phase and interprets their voltage is low by default.

It can be observed that the lowest voltages appear in the middle of the feeder, while the buses in the end, which are much closer together, keep voltages around and above 0,95 pu due to the action of the capacitors. The influence of the grid and substation in maintaining high voltages is therefore soon lost in the long lines.

Some lines appear represented with their second half in beige colour. This happens because of distributed loads: they are connected to a junction node, rather than a busbar, in the middle point of the line, as suggested by IEEE, and that splits the line in half. These distributed loads do not appear in the physical approximation of the feeder, but are edited in the schematic version.

4.2. Modelling process

All elements were modelled according to the data provided by the IEEE [22].

Elements in PowerFactory have particular data, and a type, which gives more general data on the behaviour of the same category of elements. In this project there were 5 line types, 6 load types, 2 regulator and transformer types, 3 busbar types and 1 capacitor type.

4.2.1. Grid

The External Grid provides the necessary power to the feeder. It has been modelled according to the total values of consumed active and reactive power in the network, taking into account the compensated reactive power by the capacitors in buses 844 and 848. The grid was modelled as a Slack or reference bus, with a target to maintain the buses' voltages.

In DIgSILENT, it is modelled according to figure 4.3.

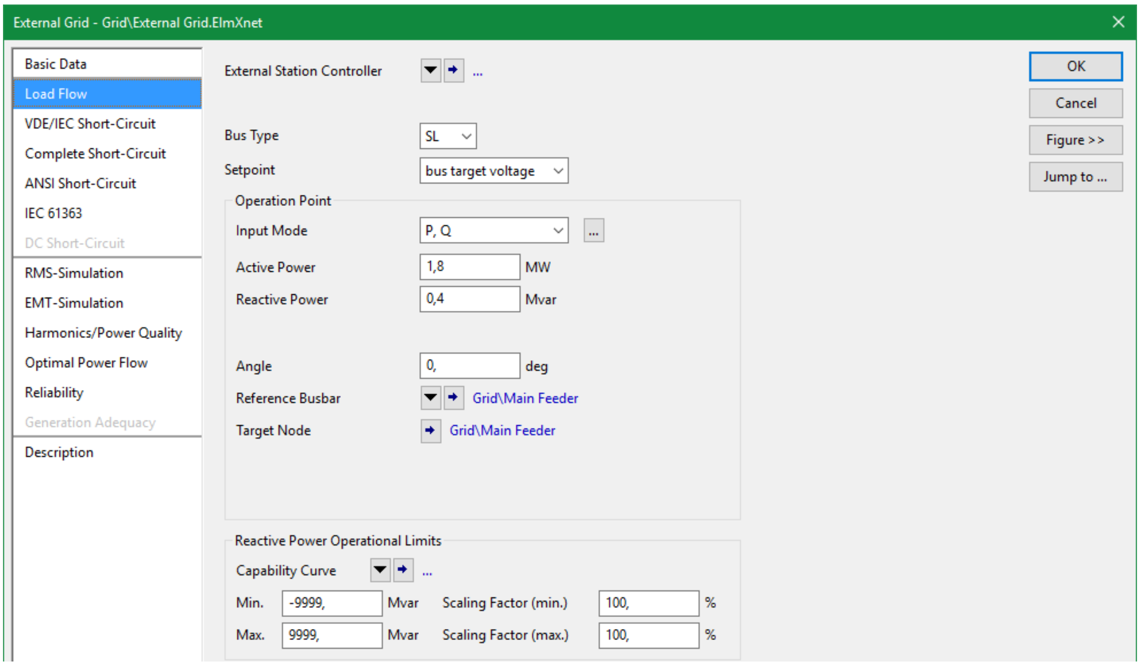

Figure 4.3. Grid data

4.2.2. Transformers

Transformers connect the areas of the network with different voltages and are sized according to the needs of the feeder. The transformers in this feeder were a substation, connecting the feeder with the grid, and an in-line transformer connecting the 4,16 kV branch to the rest of the feeder.

Transformers require their High Voltage and Low Voltage sides defined, and determining a particular Tap Changer configuration both in the item and its type helps regulating the voltage automatically.

In DIgSILENT, they are modelled according to figures 4.4 and 4.5.

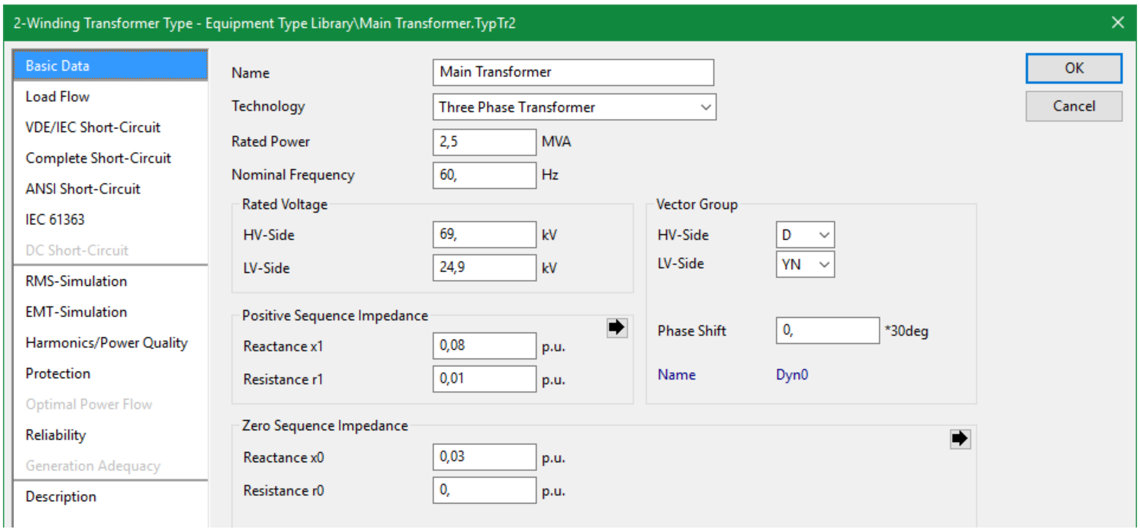

Figure 4.4. Transformer type, substation sample

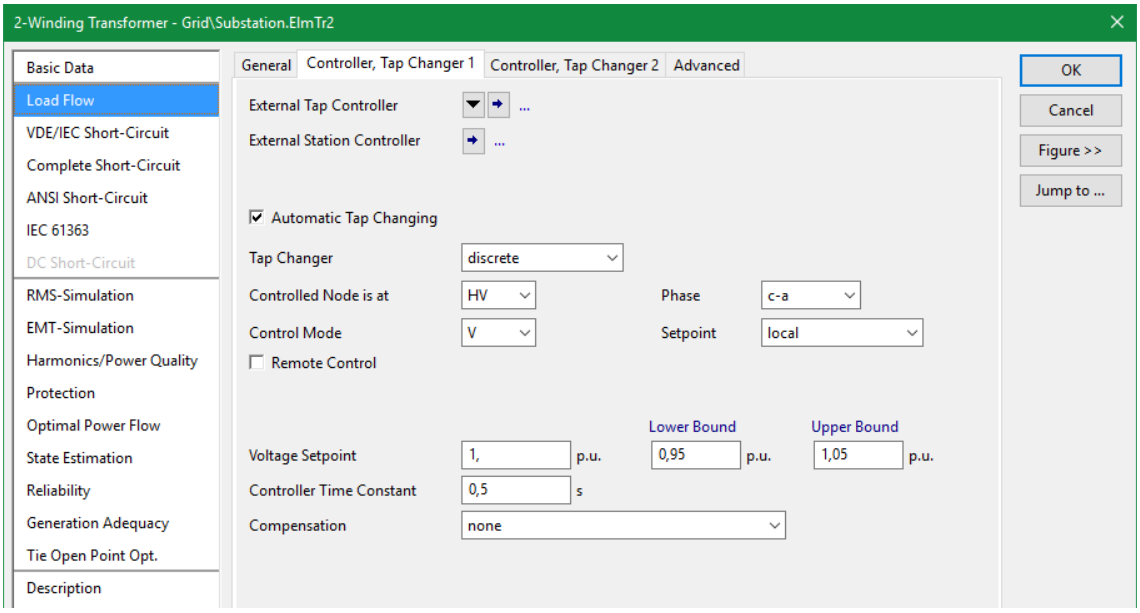

Figure 4.5. Transformer tap controller, substation sample

4.2.3. Voltage regulators

Voltage Regulators' function is to keep a good downstream voltage profile. Along this feeder they were evenly spaced to compensate for line losses. Their modelling is similar to that of an auto-transformer [23].

In DIgSILENT, they are modelled according to figures 4.6 and 4.7.

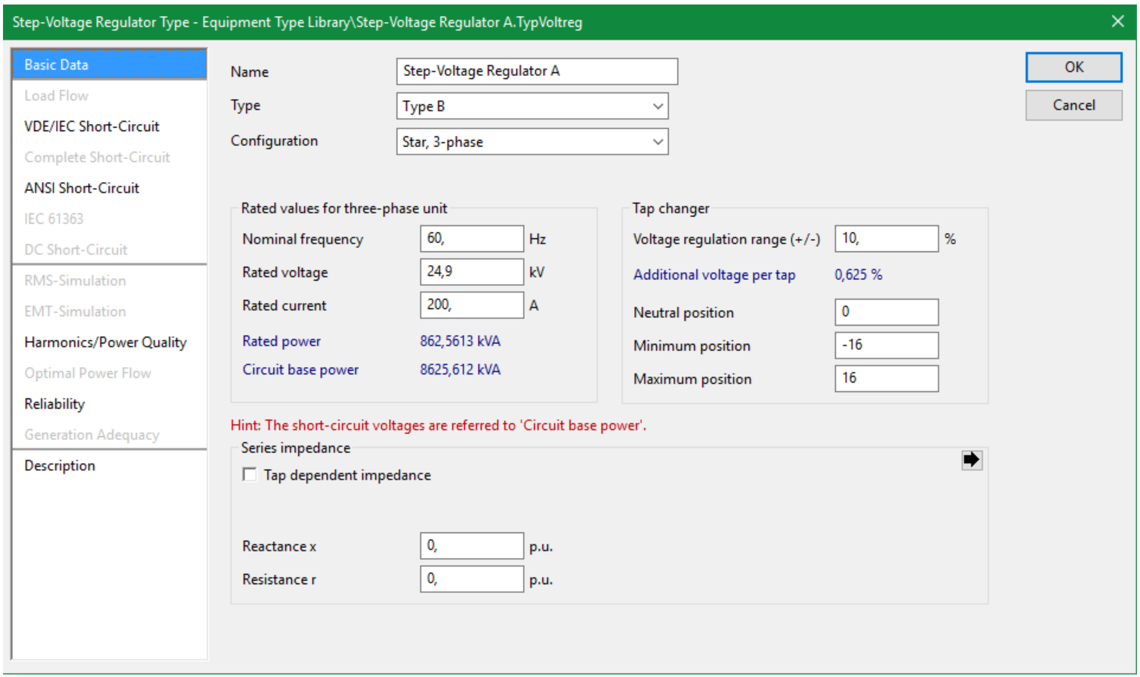

Figure 4.6. Regulator type, first regulator sample

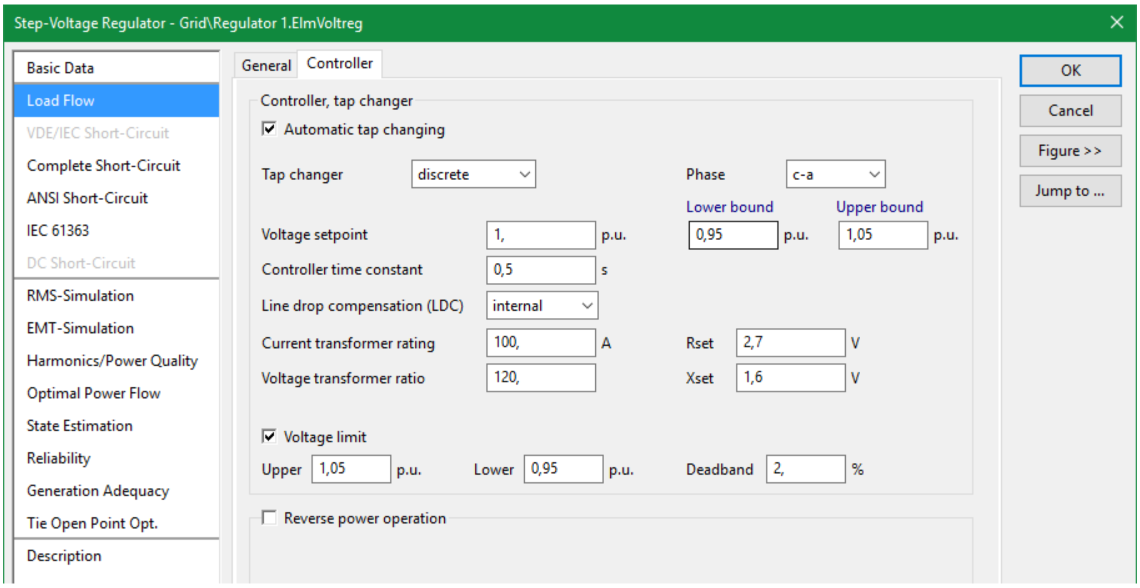

Figure 4.7. Regulator tap controller, first regulator sample

4.2.4. Loads

The main parameters required to model a load besides its type are the active and reactive power in each of its phases (figure 4.8), if it is unbalanced, and its voltage level. In this feeder there were spot loads and distributed loads. The latter were represented by placing them halfway in their line, as indicated by the IEEE.

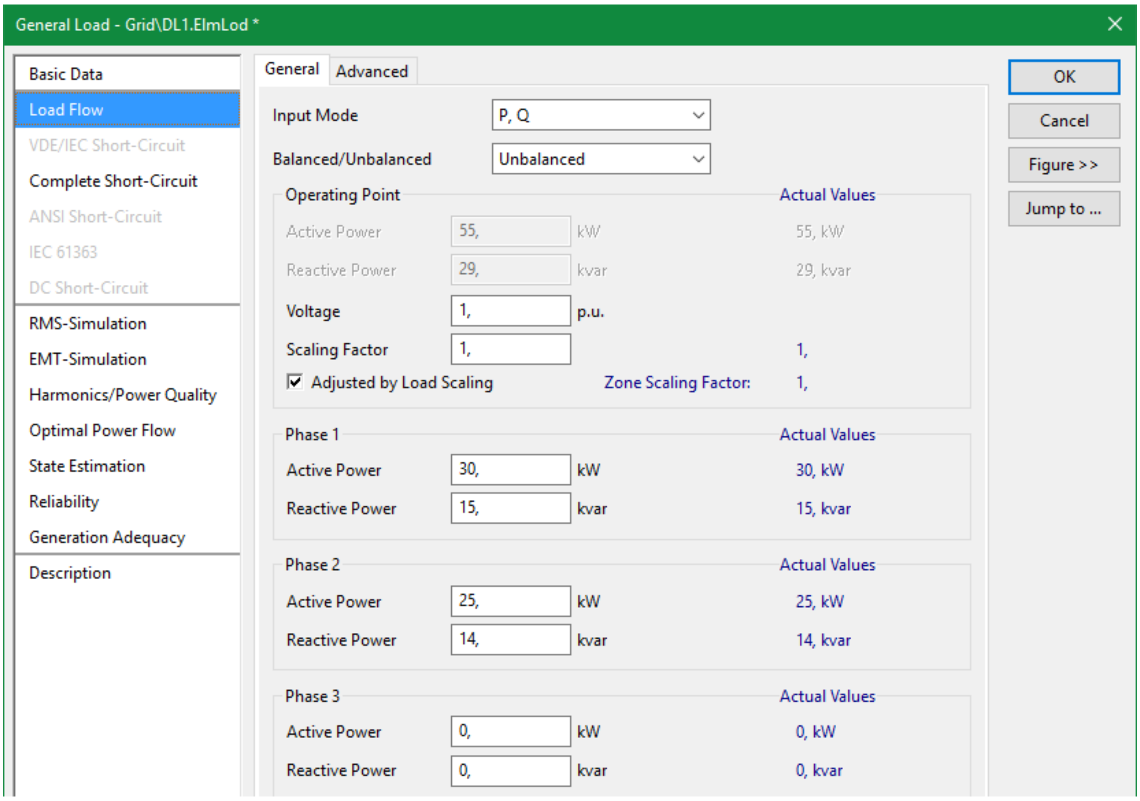

Figure 4.8. Load model, distributed load 1 sample

There exist six different types of loads: in Δ or Y configurations, and with constant power (PQ), current (I) or impedance (Z). The modelling of these is done when configuring the voltage dependency of loads by setting certain coefficients in the Load Flow section of the Load Type (figure 4.9):

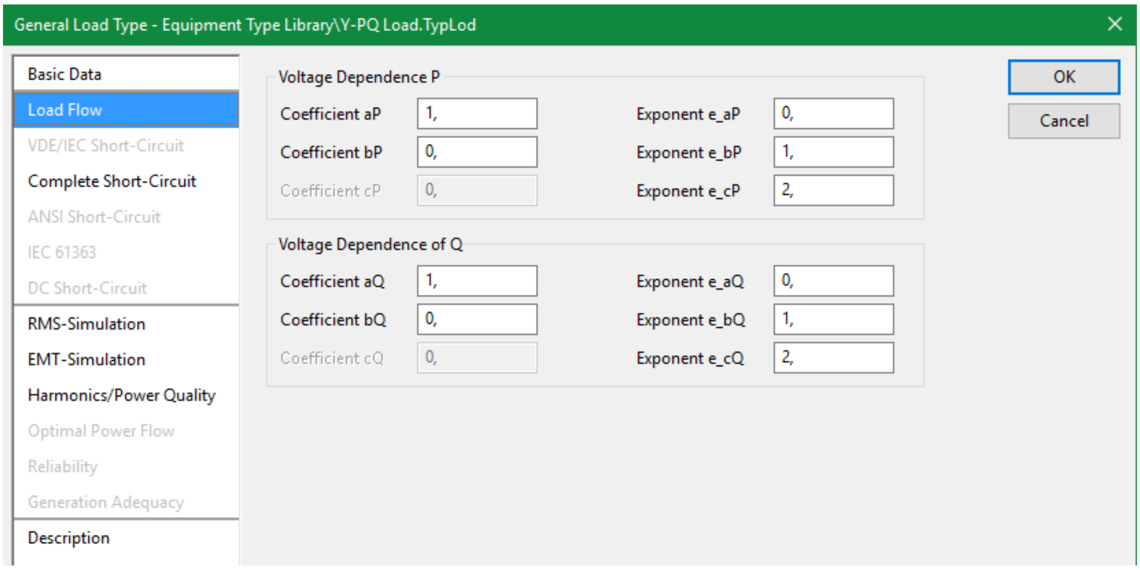

Figure 4.9. Voltage dependency configuration, PQ sample

Behind these coefficients there are certain equations. In Power Factory, voltage dependency of loads is modelled using three polynomial terms that correspond to the three different possible behaviours. The equations for active power (P) will be used as a sample, but the equations for reactive power (Q) are exactly the same:

$$P = P_0\left(aP\left(\frac{v}{v_0}\right)^{e_aP} + bP\left(\frac{v}{v_0}\right)^{e_bP} + cP\left(\frac{v}{v_0}\right)^{e_cP}\right) \tag{4.1}$$

where

$$cP = 1 - aP - bP \tag{4.2}$$

The coefficients in equations 4.1 and 4.2 must take the values described in table 4.1 to model each of the load types. For this to have effect, the option "Consider Voltage Dependency of Loads" must be selected when performing the load flow analysis.

Constant	Exponent	Value	aP	bP	cP
Power	e_aP	0	1	0	0
Current	e_bP	1	0	1	0
Impedance	e_cP	2	0	0	1

Table 4.1. Coefficients for modelling load behaviour

4.2.5. Lines

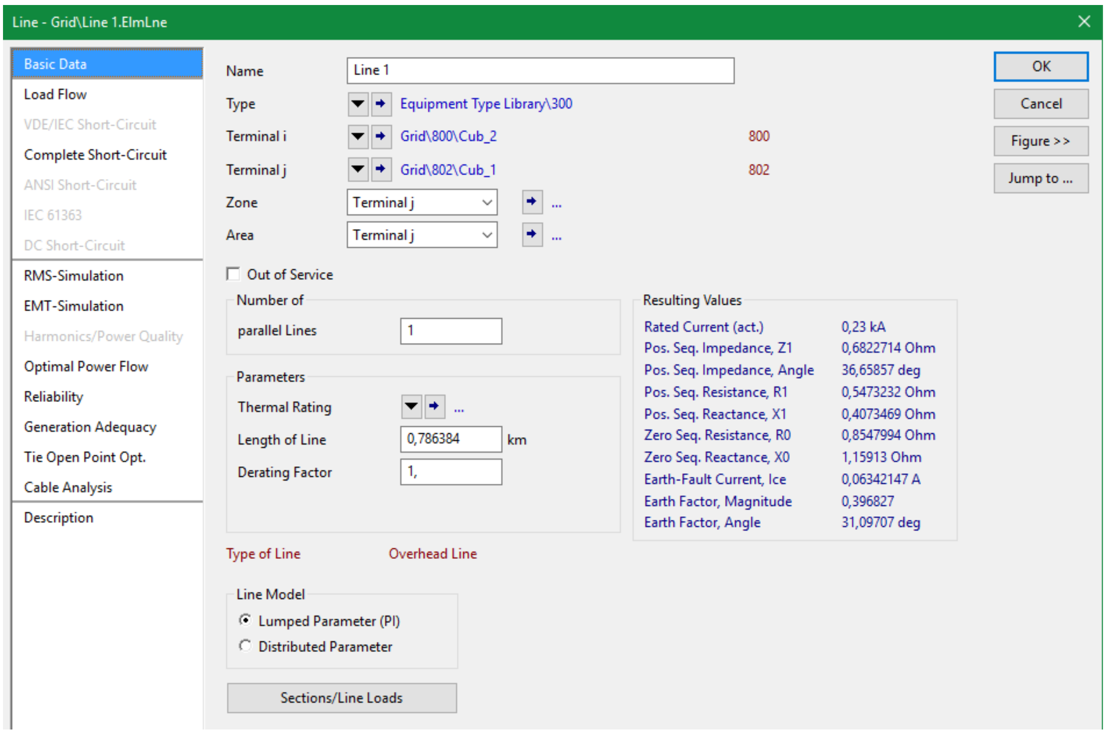

Figure 4.10. Line data, 300 type sample

The parameters defined for each particular line were length and model, as shown in figure 4.10. The lumped parameter or Π model was used.

In this feeder there were five line types, two with three phases and a neutral, used in the main line, and three with one phase and one neutral, used in some of the secondary branches. The terminals could be edited as in figure 4.11 to fit the appropriate phase in the case of single phase lines; phase a for 302 type, and phase b for 303 and 304 types.

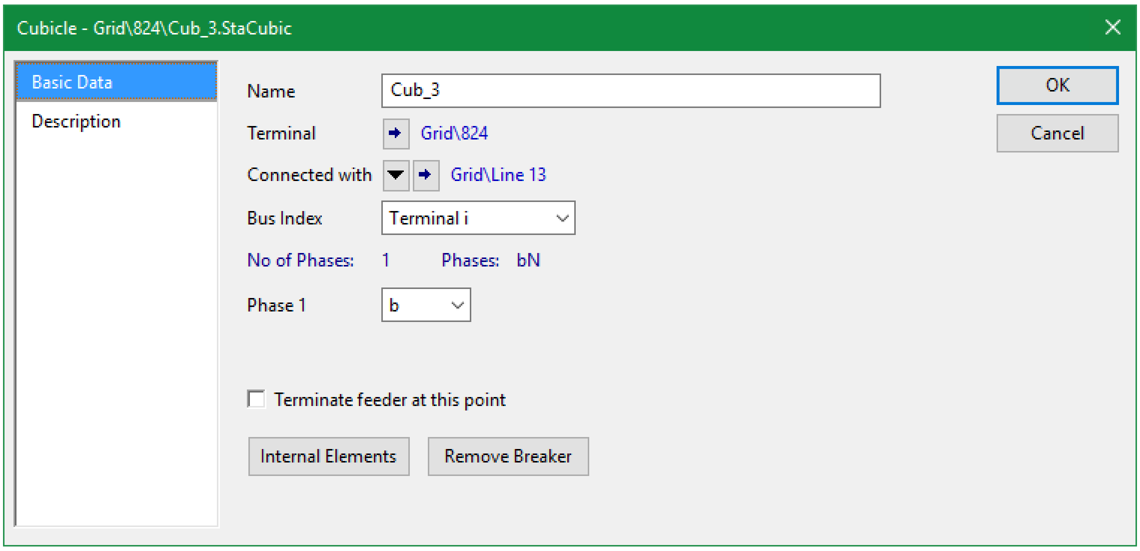

Figure 4.11. Line cub edition, Line 13 sample

In the line type configuration (figures 4.12, 4.13 and 4.14) many parameters need to be defined: line resistance, reactance and susceptance, phases, voltage level, ampacity, and cable type, material and cross section.

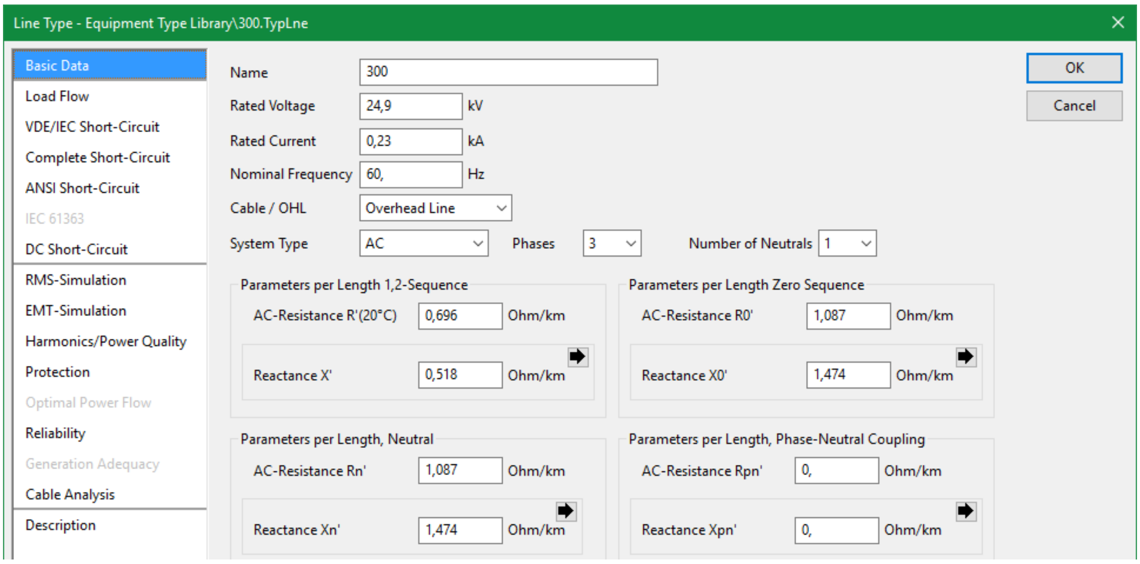

Figure 4.12. Line type Basic data, 300 type sample

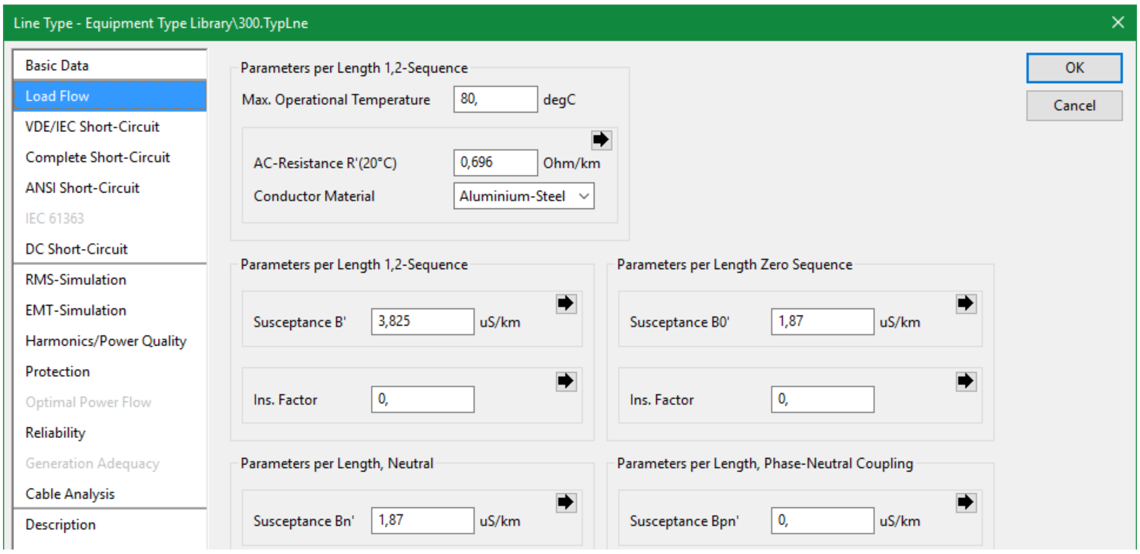

Figure 4.13. Line type Load flow, 300 type sample

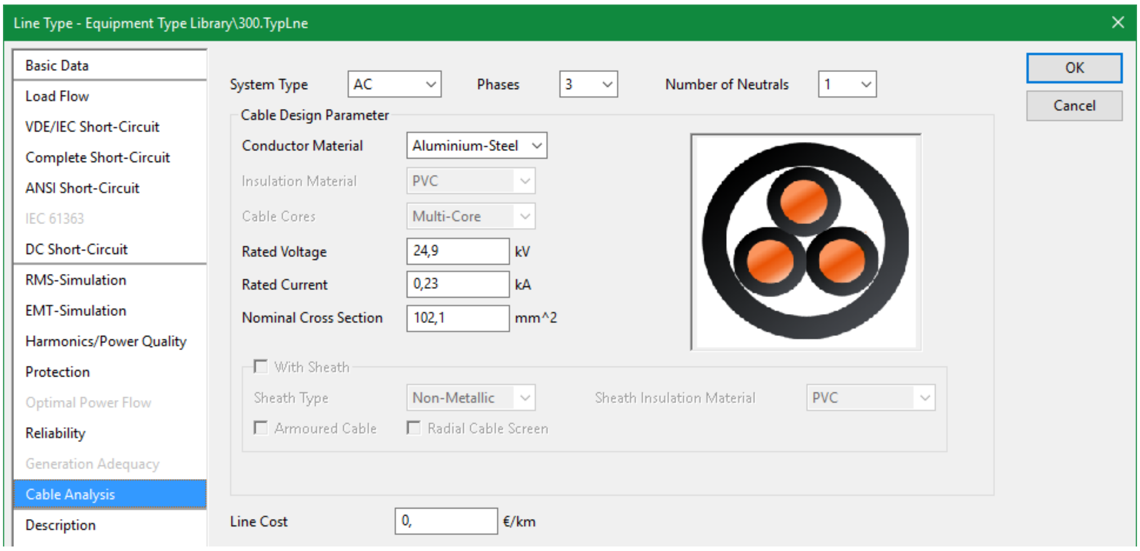

Figure 4.14. Line type Cable analysis, 300 type sample

With the guidance of Adewole's thesis [23] it was possible to translate the modelling data the IEEE [22] provided for each phase into actually implementable data in positive (11) and zero (00) sequences. The original data are detailed in Annex A. The process used was as follows:

$$Z = \begin{pmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{pmatrix} \tag{4.3}$$

$$Z_s = \frac{Z_{aa} + Z_{bb} + Z_{cc}}{3} \tag{4.4}$$

$$Z_m = \frac{Z_{ab} + Z_{ac} + Z_{ba} + Z_{bc} + Z_{ca} + Z_{cb}}{6} \tag{4.5}$$

Therefore:

$$Z = \begin{pmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{pmatrix} \tag{4.6}$$

The positive sequence impedance and zero sequence impedance will be, respectively:

$$Z_{11} = Z_{22} = Z_s - Z_m \tag{4.7}$$

$$Z_{00} = Z_s + 2Z_m \tag{4.8}$$

The final data used in the line models for each type were the ones in table 4.2:

	R_{11} (Ω/km)	X_{11} (Ω/km)	R_{00} (Ω/km)	X_{00} (Ω/km)	B_1 (μS/km)	B_0 (μS/km)
300	0,696	0,518	1,087	1,474	3,825	1,870
301	1,050	0,523	1,484	1,602	3,669	1,822
302	0,580	0,308	0,580	0,308	0,875	0,875
303	0,580	0,308	0,580	0,308	0,875	0,875
304	0,398	0,294	0,398	0,294	0,904	0,904

Table 4.2. Final line modelling data

4.2.6. Busbars

Busbars act as connection points for the different elements in the feeder. They are simple elements which only need voltage and phase technology defined.

In DIgSILENT, they are modelled according to figure 4.15.

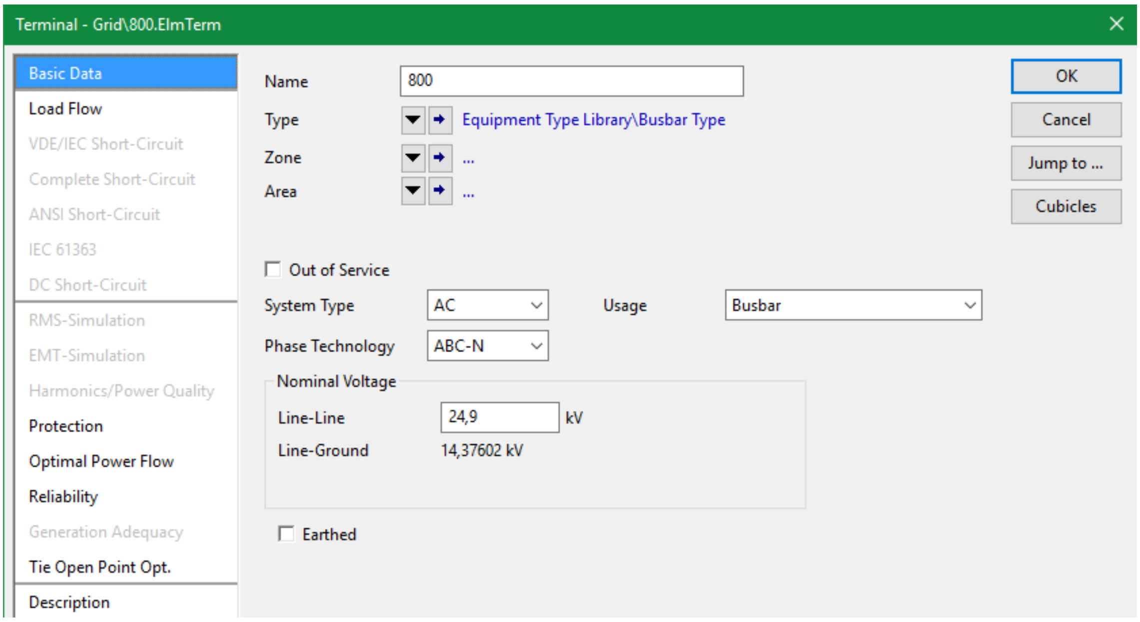

Figure 4.15. Busbar data, Bus 800 data

4.2.7. Capacitors

Capacitors provided significant reactive power compensation and helped rise the voltage of the whole system. They were simple to model, only with rated reactive power and phase technology.

In DIgSILENT, they are modelled according to figure 4.16.

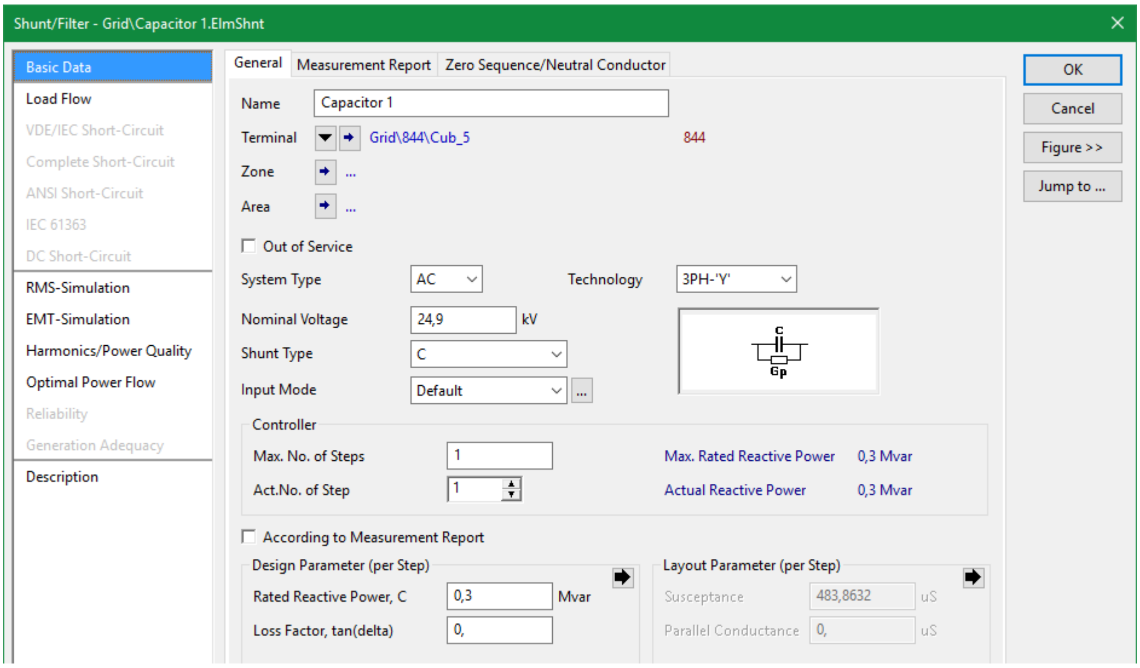

Figure 4.16. Capacitor data, Capacitor 1 sample

4.3. Analysis of results

	Results			IEEE			Relative error		
	Ua (pu)	Ub (pu)	Uc (pu)	Ua (pu)	Ub (pu)	Uc (pu)	Ua (pu)	Ub (pu)	Uc (pu)
800	0,995	0,999	1,008	1,050	1,050	1,050	5,23%	4,85%	4,01%
802	0,994	0,998	1,007	1,048	1,048	1,048	5,15%	4,77%	3,90%
806	0,993	0,998	1,007	1,046	1,047	1,047	5,08%	4,73%	3,84%
808	0,975	0,990	1,002	1,014	1,030	1,029	3,78%	3,84%	2,62%
810		0,990			1,029			3,83%	
812	0,955	0,982	0,995	0,976	1,010	1,007	2,17%	2,78%	1,14%
814	0,939	0,975	0,990	0,947	0,995	0,989	0,81%	1,91%	0,08%
816	0,921	0,957	0,971	1,017	1,025	1,020	9,44%	6,66%	4,76%
818	0,921			1,076			14,44%		
820	0,912			0,993			8,10%		
822	0,911			0,990			7,92%		
824	0,918	0,952	0,968	1,008	1,016	1,012	8,99%	6,28%	4,29%
826		0,952			1,016			6,26%	
828	0,917	0,952	0,968	1,007	1,015	1,011	8,95%	6,24%	4,25%
830	0,910	0,944	0,961	0,989	0,998	0,994	8,01%	5,46%	3,26%
832	0,928	0,960	0,981	1,036	1,035	1,036	10,45%	7,22%	5,31%
834	0,926	0,957	0,979	1,031	1,030	1,031	10,21%	7,03%	5,05%
836	0,925	0,956	0,979	1,030	1,029	1,031	10,21%	7,03%	5,04%
838		0,956			1,029			7,02%	
840	0,925	0,956	0,979	1,030	1,029	1,031	10,21%	7,04%	5,05%
842	0,926	0,957	0,979	1,031	1,029	1,031	10,21%	7,03%	5,05%
844	0,926	0,957	0,979	1,031	1,029	1,031	10,18%	7,00%	5,03%
846	0,926	0,957	0,980	1,031	1,029	1,031	10,17%	7,00%	5,01%
848	0,926	0,957	0,980	1,031	1,029	1,031	10,17%	7,00%	5,02%
850	0,921	0,957	0,972	1,018	1,026	1,020	9,45%	6,66%	4,78%
852	0,899	0,930	0,950	0,958	0,968	0,964	6,20%	3,94%	1,38%
854	0,910	0,943	0,961	0,989	0,998	0,993	7,99%	5,45%	3,24%
856		0,943			0,998			5,44%	
858	0,927	0,959	0,980	1,034	1,032	1,034	10,34%	7,14%	5,19%
860	0,925	0,957	0,979	1,031	1,029	1,031	10,21%	7,03%	5,05%
862	0,925	0,956	0,979	1,030	1,029	1,031	10,21%	7,04%	5,04%
864	0,927			1,034			10,34%		
888	0,916	0,948	0,969	1,000	0,998	1,000	8,37%	5,04%	3,11%
890	0,889	0,921	0,942	0,917	0,924	0,918	2,97%	0,23%	2,65%
Main Feeder	1,000	1,000	1,000	1,050	1,050	1,050	4,76%	4,76%	4,76%
RG10	0,921	0,957	0,972	1,018	1,026	1,020	9,46%	6,66%	4,78%
RG11	0,928	0,960	0,981	1,036	1,035	1,036	10,45%	7,22%	5,31%

Table 4.3. Voltage magnitude results compared to the IEEE standard

The results obtained for voltage magnitudes were consistently below the ones provided, many exceeding the 0,95 pu limit, as shown by table 4.3. Different grid and tap configurations in transformers and regulators were tried out, but results did not improve.

Relative errors (table 4.4) had an average of 6,99%, with the highest values in Phase a. This is due to the fact that Phase a is the most loaded, followed by Phases b and c, which leads to a higher difficulty in keeping high voltage values. If errors are compared to those of Adewole [23], who also simulated this feeder with a full Power Factory DIgSILENT licence, the average relative error is reduced a 1,12%, to 5,87%, and they are spread out through the three phases. As such, the results obtained were considered good enough to begin the optimization of the voltage profile.

	Ua	Ub	Uc	Average
IEEE				
Averages	9,53%	6,67%	4,76%	6,99%
Minimum	0,76%	1,87%	0,13%	0,92%
Maximum	14,40%	8,67%	6,81%	9,96%
Adewole's Thesis				
Averages	5,91%	6,26%	5,43%	5,87%
Minimum	0,79%	0,31%	0,36%	0,49%
Maximum	8,99%	9,81%	8,91%	9,24%

Table 4.4. Relative errors comparison

For the sake of simplicity and clarity in this study, and just as an indicator of the general behaviour of the feeder, the voltage magnitudes and their errors have been averaged in this and the following sections.

4.3.1. Problems and solutions: Modelling

The first issue that arose while modelling this network was the node limit. IEEE 34 has, with the auxiliary nodes "Main Feeder", RG10 and RG11, 37 nodes. IEEE recommends to model distributed loads as a concentrated load in the middle of their line. As IEEE 34 has 19 distributed loads, there would be 56 nodes, surpassing the 50 nodes allowed by PF4T license. It was tried to divide the loads by half and place each in the end node of the corresponding line, but the resulting voltage levels were too low. Finally, an expansion of the license was asked to and given by DIgSILENT to allow for more nodes.

The unbalanced nature of the network, having some three phase branches and some single phase, and loads unevenly distributed among the three phases as well, complicated the modelling process.

Diverse issues in modelling the transformers' and regulators' tap changers, which resulted in an in-depth consultation of the technical references provided by Power Factory in order to model them as accurately as possible.

Lines' configurations and lengths provided by IEEE were in the American unit system and needed to be translated to the International System. Configurations in their original forms are detailed in Annex A. The conversion factors used are detailed in table 4.5.

American	International
feet (ft.)	m
1	0,3048
mile	km
1	1,60934
inch	cm
1	2,54

Table 4.5. Conversion factors

Finally, a clear issue was affecting the network, as voltage values remained around 0,8 pu, but it was proving futile to find out the cause. Adeymi Charles Adewole was contacted through LinkedIn and asked for help. He, after observing the file, pointed out a reactive power deficiency in the capacitors, and with that, the model was finished.

5. VOLTAGE CONTROL STUDY

Power networks are usually inductive due to their main elements: lines and transformers. The more inductive reactance is present, the greater the voltage phase angle will be, and, consequently, the losses. The network of our study has two transformers and very long lines, which, together with its uneven loading, make its voltage low and thus in need reactive power compensation [17].

5.1. Selection of reactive power compensators

The effectiveness of reactive power compensation and voltage improvement devices depends on their number, size, placement and control schemes [15], which are unique to each project. In this study it was decided to limit the analysis to capacitor banks and StatVars, given that DIgSILENT Power Factory did not have StatCom models nor allowed dynamic simulations.

5.2. Static analysis

The weakest nodes, identified as the ones with the lowest voltages [7], are 852 and 890. The effect of both capacitor and StatVar systems on said nodes was tested on the feeder.

	Ua	Ub	Uc	Average
Original				
Averages	9,33%	6,47%	4,72%	6,84%
Minimum	0,81%	0,23%	0,08%	0,37%
Maximum	14,44%	7,22%	5,31%	8,99%
StatVar				
Averages	4,81%	3,08%	2,76%	3,55%
Minimum	0,06%	0,02%	0,14%	0,07%
Maximum	10,30%	8,34%	10,51%	9,72%
C				
Averages	12,15%	15,09%	16,71%	14,65%
Minimum	0,03%	0,24%	0,99%	0,42%
Maximum	30,66%	33,90%	36,09%	33,55%

Table 5.1. Relative errors respect the IEEE values with StatVArs and capacitors

It was decided to provide the same amount of reactive power provided by the grid, 0,4 MVAr, and distribute it between two devices placed on each of the weakest buses, in 4 steps of 0,05 MVAr each device.

From the results in table 5.1 it is clear that the StatVar provides a better service. Minimum, maximum and average relative errors respect the official IEEE values are always lower with the StatVars.

Also, the average voltage provided by the combination of capacitors is excessively high, surpassing the 1,05 pu limit, while the StatVar keeps close to 1 pu and has a much more equilibrated voltage level across the network, being its standard deviation the lowest of all, as shown in table 5.2.

	IEEE	Base	StatVar	C
Average	1,019	0,954	0,994	1,145
Std. Dev.	0,027	0,023	0,012	0,059

Table 5.2. Average voltages and standard deviations for the unbalanced network

5.3. Quasi-Dynamic analysis

To refine the voltage control system, it has been tested against variations of demand. The demand of Spain in the day July 7th of 2017, obtained from the Red Eléctrica de España online site [24], has been levelled to per unit, so that the peak in demand corresponds to 1 pu. The resulting curve is plotted in figure 5.1.

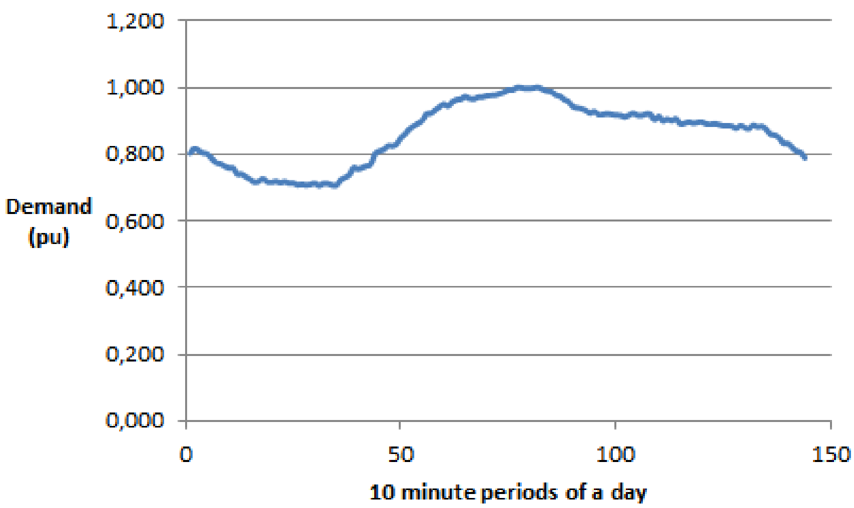

Figure 5.1. Levelled demand for a typical summer day

That day was chosen because, later in the study, PV systems will be added to the network and a standard solar production curve is desired. The average coefficient for each hour, in a total of 24, has been applied to all the loads in succession, making use of the Scaling Factor and checking the "Adjusted by Load Scaling" and "Feeder Load Scaling" options in the load model and load flow windows respectively.

The 24 simulations were then repeated for the StatVar configuration and capacitor configuration. The behaviour of the voltage phases in all the nodes was recorded for all 48 simulations. Voltages have been averaged per hour and phase.

As it can be observed in figure 5.2, the StatVars are able to keep all the phases in a stable value, with the average being almost constant.

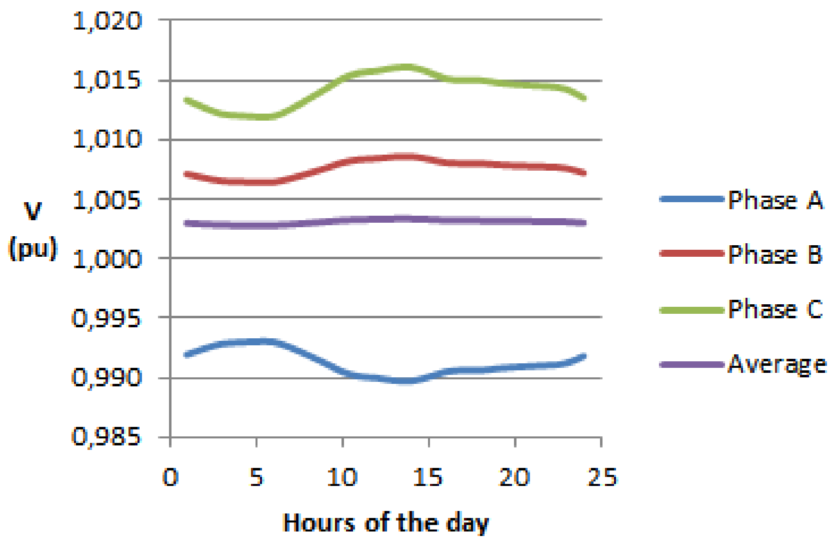

Figure 5.2. Average voltages throughout the day with the StatVar configuration

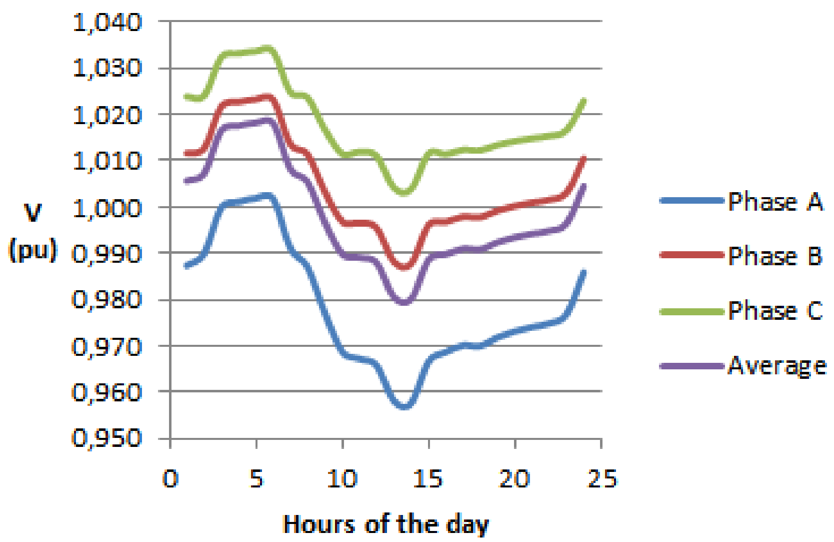

Figure 5.3. Average voltages throughout the day with the capacitor configuration

The capacitors, their result plotted in figure 5.3, provide a much more unstable voltage development. It has a great Ferranti effect [16] in the night hours, while in the StatVar it was very slight in Phase A, and the voltage progresses in a stepped manner, showing the capacitor's inability to control the network smoothly.

The ability of the StatVars to control reactive power is manifested in the steps they had to deviate from their original configuration (4 of 0,05 MVAr) to meet the requirements of the network. This number varies proportionally with the demand (figure 5.4), as more reactive power compensation would be needed in those hours. This necessity is also more pronounced in node 852, which is in the middle of the line and under more stress, as opposed to 890, which is at the end of a branch.

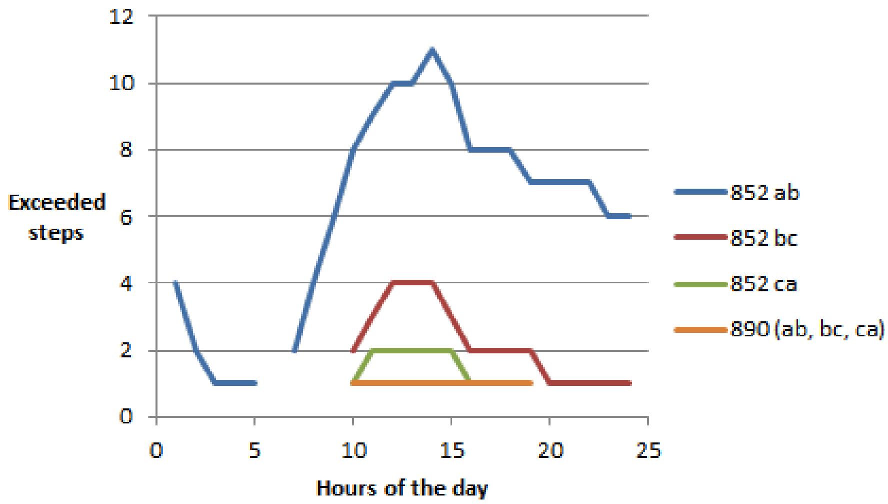

Figure 5.4. Exceeded steps by the StatVars

5.4. Distributed generation

Since our prime objective is to adapt the network to the penetration of distributed generation, the same configurations have been tested against a 50% penetration, i.e., distributed generation of half the load in each loaded node. As photovoltaic technology is the main one used for this purpose, it is the one modelled.

Generation data was obtained in the same way as demand. Photovoltaic generation data from the same day (July 7th of 2017) were extracted from the REE website [24] and levelled to per unit. The 50% penetration was achieved by multiplying the levelled generation curve plotted in figure 5.6 by 0,5 and applying the result to the Scaling Factor in the model in figure 5.5.

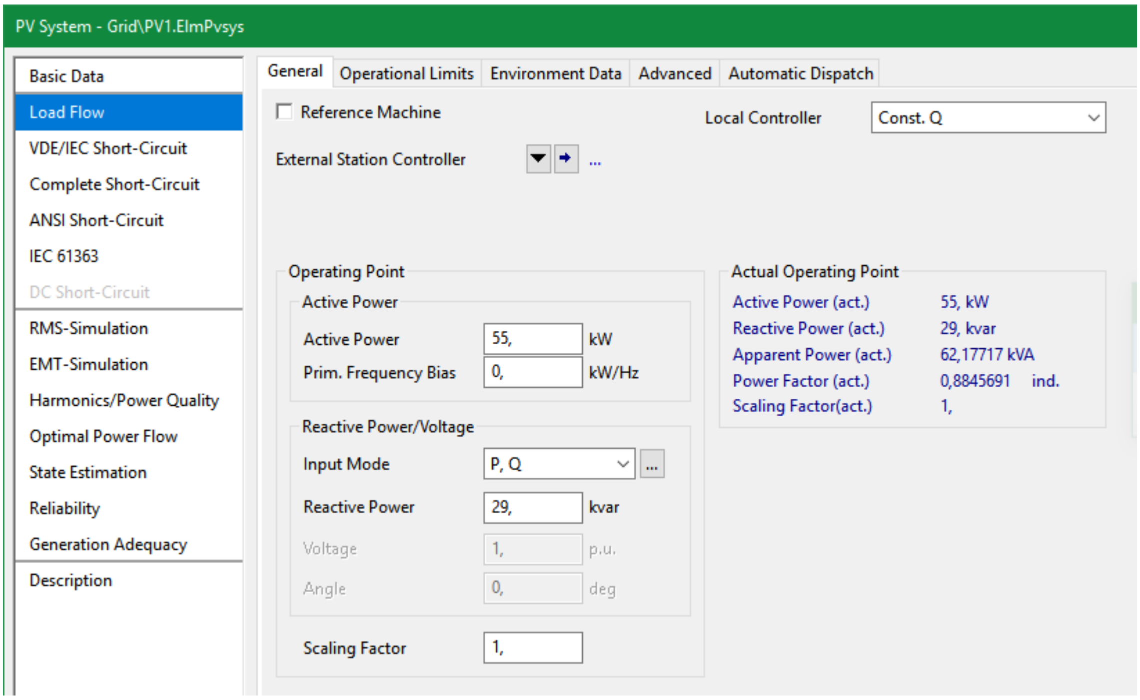

Figure 5.5. Photovoltaic panel load flow, PV1 sample

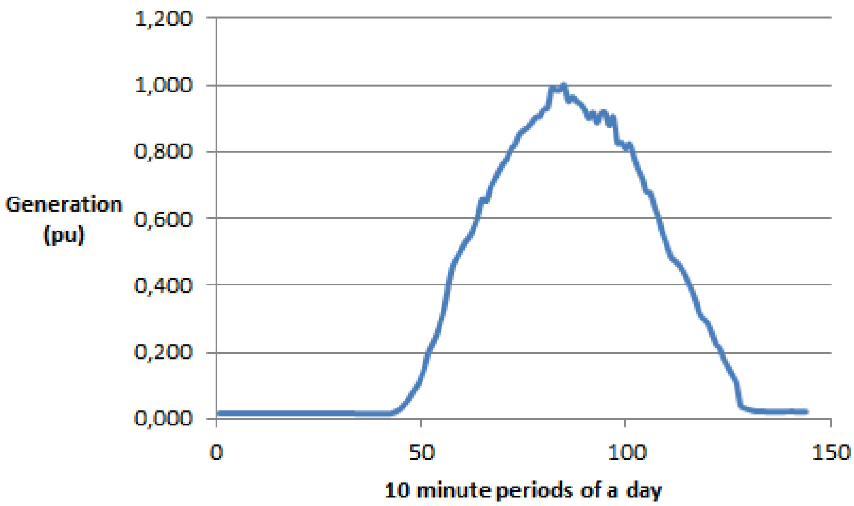

Figure 5.6. Levelled PV generation for a typical summer day

The same analysis were performed to the new network: static and quasi-dynamic with both StatVars and capacitors.

	IEEE	Base	StatVar	C
Average	1,019	0,954	1,003	0,980
Std. Dev.	0,027	0,023	0,010	0,016

Table 5.3. Average voltages and standard deviations

Again, the StatVar proved to be the best option for reactive power control. Its average voltage is closest to 1 pu, and its standard deviation is the lowest, as shown in table 5.3.

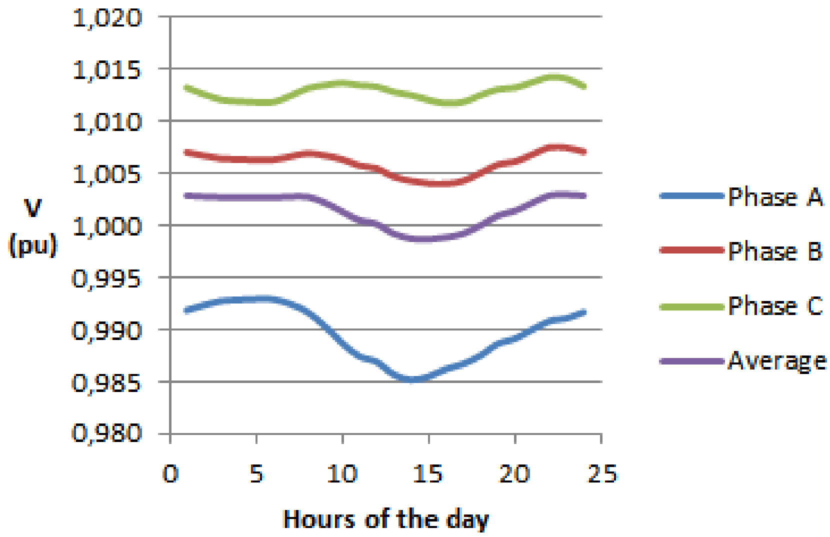

Figure 5.7. Average voltages throughout the day with the StatVar configuration

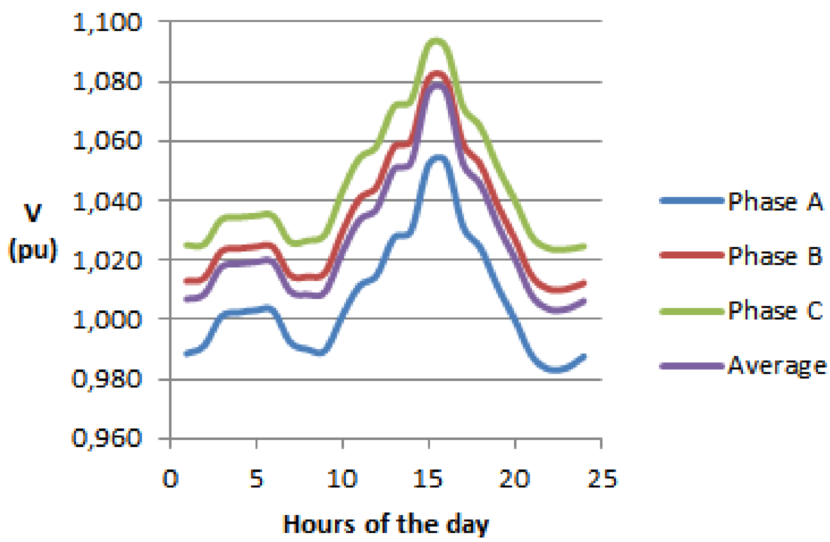

Figure 5.8. Average voltages throughout the day with the capacitor configuration

The quasi-dynamic simulations produced similar results to the previous situation without PV. The StatVars kept voltage stable (figure 5.7), although the three phases consistently although slightly dropped their voltage in the middle of the day, corresponding to the peak of solar generation.

This effect is described by Barker [14], by which the introduction of distributed generation downstream of voltage regulators causes said regulators to perceive a lower load downstream in the line and therefore sets a lower voltage requirement.

In addition, the step limit was rarely exceeded, showing how the StatVar can even improve its performance in the presence of other dynamic elements such as PV panels.

The capacitors, on the other hand, rose the voltage proportionally to the generation and alarmingly out of range (figure 5.8), beyond the 1,05 pu mark in 5 hours, unable to trip off when there is reactive power excess from an external source. The stepped nature of the voltage curve persists.

It can be therefore concluded that a StatVar is preferred to control reactive power.

5.5. Balanced network

The IEEE 34 Node Test Feeder is a very unbalanced and unstable network, with long lines and unsymmetrical loads that make its analysis difficult. In order to perform a more in depth analysis the feeder has been modified by making all of its lines three-phase and distributing the loads evenly among the three phases as well. This allows the DIgSILENT software to perform sensitivity analysis, as well as PV and QV curves for specific nodes. These curves are relevant to the study of voltage stability in the system.

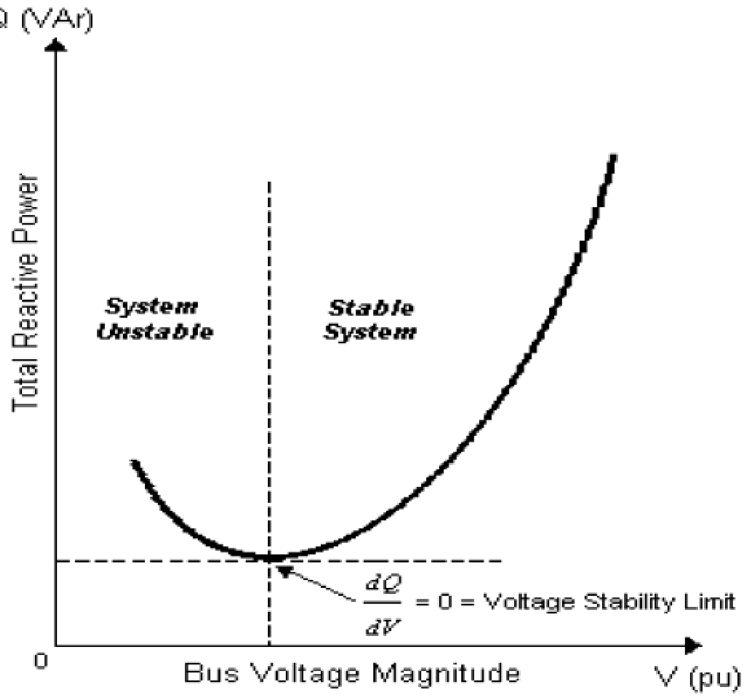

Figure 5.9. Typical QV curve [25]

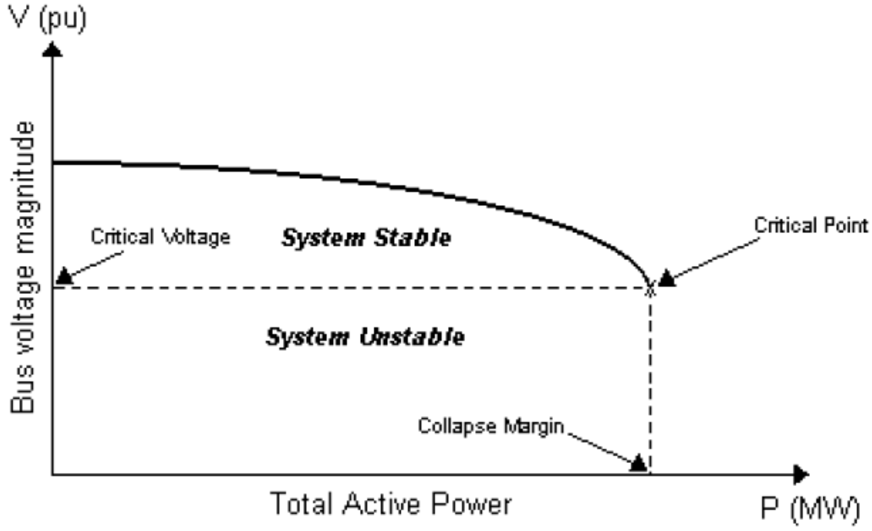

Figure 5.10. Typical PV curve [25]

The sole change from unbalanced to balanced shows a clear improvement in the voltage profile, as seen in table 5.4.

	V (pu)			V (pu)	
	Bal.	Non-Bal.		Bal.	Non-Bal.
800	1,001	1,001	840	0,955	0,953
802	1	1	842	0,955	0,954
806	1	0,999	844	0,955	0,954
808	0,990	0,989	846	0,955	0,954
810	0,990	0,99	848	0,956	0,954
812	0,978	0,977	850	0,951	0,95
814	0,969	0,968	852	0,927	0,926
816	0,951	0,95	854	0,939	0,938
818	0,951	0,921	856	0,939	0,943
820	0,948	0,912	858	0,956	0,955
822	0,948	0,911	860	0,955	0,954
824	0,947	0,946	862	0,955	0,953
826	0,947	0,952	864	0,956	0,927
828	0,947	0,946	888	0,945	0,944
830	0,940	0,938	890	0,919	0,918
832	0,957	0,956	M.F.	1	1
834	0,955	0,954	RG10	0,951	0,95
836	0,955	0,953	RG11	0,957	0,956
838	0,955	0,956			

Table 5.4. Voltage improvement in balanced network

	dϕ/dP deg/MW	dϕ/dQ deg/Mvar	dv/dP p.u./MW	dv/dQ p.u./Mvar
800	1,832	-0,232	0,005	0,033
802	1,832	-0,232	0,005	0,033
806	1,832	-0,232	0,005	0,033
808	1,832	-0,231	0,005	0,033
810	1,832	-0,231	0,005	0,033
812	1,833	-0,228	0,005	0,034
814	1,833	-0,225	0,005	0,034
816	1,833	-0,225	0,005	0,033
818	1,833	-0,225	0,005	0,033
820	1,833	-0,225	0,005	0,033
822	1,833	-0,225	0,005	0,033
824	1,833	-0,226	0,005	0,033
826	1,833	-0,226	0,005	0,033
828	1,833	-0,226	0,005	0,033
830	1,833	-0,228	0,005	0,033
832	1,832	-0,231	0,006	0,035
834	1,832	-0,231	0,006	0,035
836	1,832	-0,231	0,006	0,035
838	1,832	-0,231	0,006	0,035
840	1,832	-0,231	0,006	0,035
842	1,832	-0,231	0,006	0,035
844	1,832	-0,231	0,006	0,035
846	1,832	-0,231	0,006	0,035
848	1,832	-0,231	0,006	0,035
850	1,833	-0,225	0,005	0,033
852	1,832	-0,231	0,005	0,034
854	1,833	-0,228	0,005	0,033
856	1,833	-0,228	0,005	0,033
858	1,832	-0,231	0,006	0,035
860	1,832	-0,231	0,006	0,035
862	1,832	-0,231	0,006	0,035
864	1,832	-0,231	0,006	0,035
888	1,835	-0,211	0,006	0,035
890	1,837	-0,200	0,006	0,035
Main Feeder	0,000	0,000	0,000	0,000
RG10	1,833	-0,225	0,005	0,033
RG11	1,832	-0,231	0,006	0,035

Table 5.5. Voltage sensitivities

Voltage instability is defined as the voltage drop with the increase of reactive power due to the inability of the system to meet the demand for reactive power. This can be due to a change in operating conditions, an increase of the demand or a disturbance [25]. This can be clearly observed in figure 5.9, where the derivative of Q respect V represents the minimum reactive power required for a stable operation of the system. PV curves are also an indicator of instability, showing the maximum active power the system is capable of handling without the voltage collapsing, pointed as the critical point in figure 5.10.

Taking into account the buses with the lowest voltages and highest sensitivities (tables 5.4 and 5.5 respectively), five were selected to be studied:

- 800, as benchmark
- 822 and 848, at the end of branches
- 852 and 890, the most critical

As it can be seen in figures 5.11 and 5.12, bus 800 is the most stable one, with the lowest reactive power required and a very constant voltage despite active power increase.

On the other hand, bus 890 is the most unstable. Its voltage varies greatly with low reactive power variations, and its reactive power limit is the highest at -0,7 MVAr. It is also the bus with the steepest slope in the PV curve, which shows a great sensitivity to active power variations, and it is consequently the first of the five to reach the instability limit of 0,5 pu, at 3,32 MW. Bus 852 is the second most critical, for similar reasons. They are both the same most critical buses as in the unbalanced network study and will be the focus of the reactive power control optimization in the balanced case.

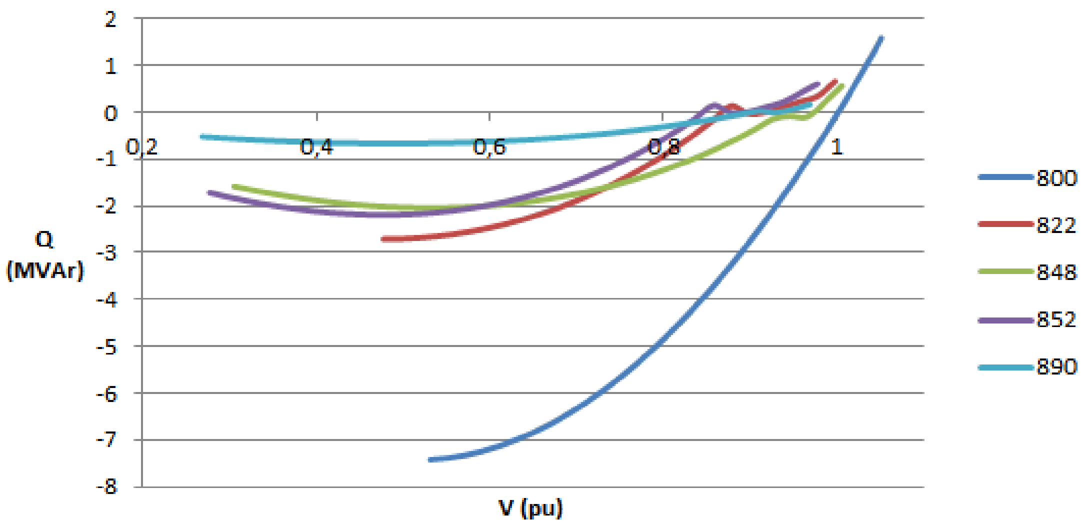

Figure 5.11. QV curve of the selected nodes

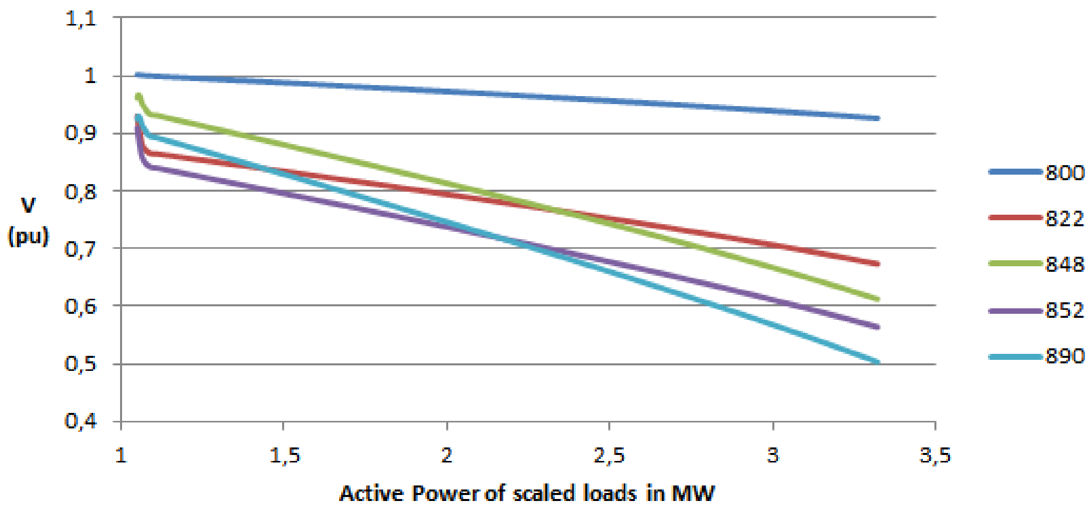

Figure 5.12. PV curve of the selected nodes

Although, it is noteworthy that the critical reactive power limit of all the buses is below zero, showing a very stable network globally, that does not require reactive power, but can deliver it.

5.5.1. Optimization of the balanced network

The same configurations of capacitors and StatVars described in section 5.2 were simulated on the balanced network because, as described previously, the weakest nodes of the network remain the same as in the unbalanced network. Two interesting developments are found.

The first, shown in table 5.6, confirms what the reactive power control in the unbalanced network revealed: voltage magnitude largely exceeds the 1,05 pu limit in all the buses, except for the Main Feeder where the grid connects, in the capacitors case. In the StatVars case the voltage stays close to the 1 pu value. Thus, they are much more fitted to managing voltage in this network.

The second, shown in table 5.7, is one that could not have been observed until now due to the unbalance of the three phases. The voltage angles with the capacitors are negative and become lower the farther away from the grid connection, while with the StatVars the angles are positive and higher the farther away from the grid connection. These leading angles show the capacitive nature of the balanced network.

Sensitivities remain the same between capacitors and StatVars cases, but they do differ from the sensitivities of the balanced network without reactive power control. The conclusion is that voltage magnitude is much less sensitive to variations in both active and reactive power, while the sensitivity of the voltage angle is greater, and actually becomes positive for variations of reactive power.

	C		StatVar	
	V (pu)	Ang (deg)	V (pu)	Ang (deg)
800	1,061	-0,069	0,987	1,201
802	1,063	-0,152	0,987	1,249
806	1,064	-0,207	0,987	1,281
808	1,082	-1,216	0,989	1,884
810	1,082	-1,216	0,989	1,884
812	1,102	-2,329	0,992	2,600
814	1,119	-3,167	0,994	3,179
816	1,231	-3,179	0,988	3,187
818	1,231	-3,179	0,988	3,187
820	1,231	-3,184	0,988	3,182
822	1,231	-3,184	0,988	3,182
824	1,237	-3,540	0,990	3,451
826	1,237	-3,540	0,990	3,451
828	1,237	-3,570	0,990	3,473
830	1,249	-4,276	0,994	4,006
832	1,156	-5,505	1,000	4,995
834	1,159	-5,770	1,004	4,719
836	1,159	-5,771	1,004	4,717
838	1,159	-5,771	1,004	4,717
840	1,159	-5,771	1,004	4,716
842	1,159	-5,776	1,004	4,712
844	1,160	-5,809	1,005	4,678
846	1,160	-5,858	1,005	4,628
848	1,160	-5,865	1,005	4,621
850	1,231	-3,168	0,988	3,179
852	1,271	-5,505	1,000	4,995
854	1,250	-4,293	0,994	4,019
856	1,250	-4,294	0,994	4,019
858	1,157	-5,626	1,002	4,868
860	1,159	-5,771	1,004	4,717
862	1,159	-5,771	1,004	4,717
864	1,157	-5,626	1,002	4,868
888	1,193	-5,369	0,988	6,918
890	1,254	-6,612	1	10,520
Main Feeder	1	0	1	0
RG10	1,231	-3,167	0,988	3,179
RG11	1,156	-5,505	1	4,995

Table 5.6. Voltages with capacitors compared to voltages with StatVars

	With Q control				Without Q control			
	dϕ/dP deg/MW	dϕ/dQ deg/Mvar	dV/dP p.u./MW	dV/dQ p.u./Mvar	dϕ/dP deg/MW	dϕ/dQ deg/Mvar	dV/dP p.u./MW	dV/dQ p.u./Mvar
800	1,860	-0,217	0,002	0,019	1,832	-0,232	0,005	0,033
802	1,862	-0,199	0,002	0,019	1,832	-0,232	0,005	0,033
806	1,864	-0,187	0,002	0,019	1,832	-0,232	0,005	0,033
808	1,887	0,044	0,002	0,015	1,832	-0,231	0,005	0,033
810	1,887	0,044	0,002	0,015	1,832	-0,231	0,005	0,033
812	1,916	0,316	0,001	0,011	1,833	-0,228	0,005	0,034
814	1,939	0,536	0,001	0,008	1,833	-0,225	0,005	0,034
816	1,939	0,539	0,001	0,007	1,833	-0,225	0,005	0,033
818	1,939	0,539	0,001	0,007	1,833	-0,225	0,005	0,033
820	1,939	0,539	0,001	0,007	1,833	-0,225	0,005	0,033
822	1,939	0,539	0,001	0,007	1,833	-0,225	0,005	0,033
824	1,951	0,657	0,001	0,006	1,833	-0,226	0,005	0,033
826	1,951	0,657	0,001	0,006	1,833	-0,226	0,005	0,033
828	1,952	0,667	0,001	0,006	1,833	-0,226	0,005	0,033
830	1,977	0,904	0	0,004	1,833	-0,228	0,005	0,033
832	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
834	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
836	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
838	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
840	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
842	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
844	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
846	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
848	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
850	1,939	0,536	0,001	0,007	1,833	-0,225	0,005	0,033
852	2,022	1,339	0	0	1,832	-0,231	0,005	0,034
854	1,977	0,910	0	0,004	1,833	-0,228	0,005	0,033
856	1,977	0,910	0	0,004	1,833	-0,228	0,005	0,033
858	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
860	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
862	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
864	2,022	1,339	0	0	1,832	-0,231	0,006	0,035
888	2,022	1,339	0	0	1,835	-0,211	0,006	0,035
890	2,022	1,339	0	0	1,837	-0,2	0,006	0,035
Main Feeder	0	0	0	0	0	0	0	0
RG10	1,939	0,536	0,001	0,007	1,833	-0,225	0,005	0,033
RG11	2,022	1,339	0	0	1,832	-0,231	0,006	0,035

Table 5.7. Voltages with and without reactive power compensation

5.6. Analysis of results

5.6.1. Device selection

The initial static analysis produced better voltage results for the StatVar configuration, with lower relative errors respect the IEEE results than both the original case and the capacitor case. They are also able to keep an average voltage closest to 1 pu and the lowest standard deviation of the four cases, which shows more balanced levels across the network. This prevents large voltage imbalances that may result in instability in a dynamic situation.

Quasi-dynamic, 24-hour analysis for both StatVars and capacitors in the same configurations as for the static case gave more comprehensive results that nonetheless reinforced the ones obtained in the static analysis.

StatVars kept voltage stable with voltage variations of 0,004 pu throughout the day at most and only a slight Ferranti effect on phase A that was compensated by the other two. On the other hand, capacitors caused a voltage peak difference of 0,04 pu. They were not able to operate dynamically properly, as shown by the stepped nature of the curves and that all phases shared, unable to compensate each other.

The same analyses were performed to the system with added distributed generation of half the loads. The observations for both static and quasi-dynamic analyses are rather similar to the ones for the network without distributed generation. However, the behavior of the curves is the opposite of those.

StatVars still produced a smoother curve than capacitors, but they dropped the voltage in the maximum solar production hours, as an effect of the interaction of distributed generation with voltage regulators. Capacitors double their voltage peak difference to 0,08 pu and kept voltage above the allowed limits for a considerable period of time. They rise the voltage instead of dropping it as in the case without generation, showing again that distributed generation and reactive power control do not behave well together unless some smart management techniques are applied.

In conclusion, StatVars are, in a technical level, better fitted to control the reactive power and voltage in an electrical grid. However, different combinations of StatVars, capacitors and StatComs on different nodes that may improve these results fall out of the range of this project and should be the subject of further research in order to find the best configuration.

5.6.2. Network configuration

The sensitivity static study on the balanced network confirmed two things: that StatVars stabilize the network while capacitors make it unstable, and the assumption that 852 and 890 nodes were the weakest of the network. Their QV curves they had the highest reactive power limits and voltage variabilities, and their PV curves achieved their critical points with the lowest active power increase. Although, bus 848 was rather close to bus 852.

Buses 890 and 848, as shown in figure 5.13 are located on the end of branches. They are some of the farthest nodes from the grid connection, 890 even behind a step-down transformer, which makes them vulnerable to fluctuations. Bus 852, on the other hand, is an in-line bus. It is after a very long line and acting as a three-way connection point, and in the original simulation had the lowest voltage of the non-branch buses.

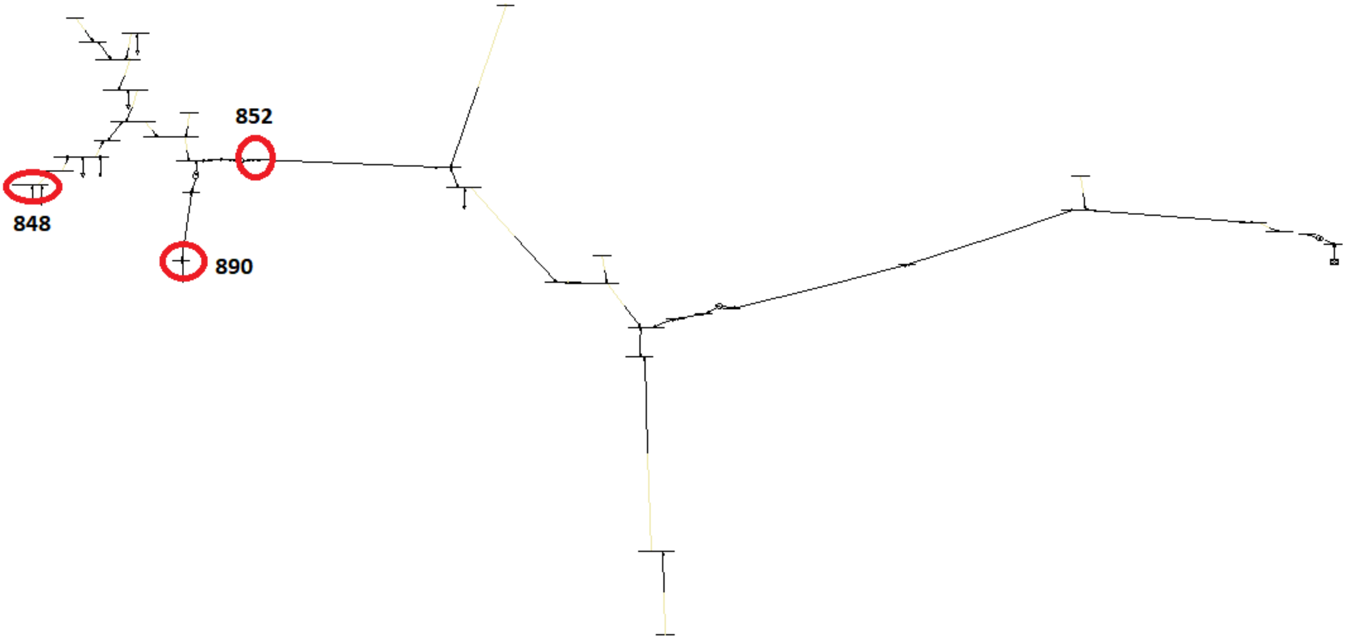

Figure 5.13. Critical nodes of the network

What can be concluded from this, as well as from the documentation research carried out throughout this project, is that radial feeder topologies are more difficult to manage and need significant restructuring to be suitable for smart grid technology and management. Each node must be connected to at least two other nodes, to avoid isolation and line congestion, and streamline the energy flow, guaranteeing its reaching all nodes in the network. These modifications fall as well out of the range of the present project, but consist the next step in this research.

5.6.3. Problems and solutions: Study

The main obstacle while performing this study was the amount of information the simulations produced and how to handle it. First, it was decided that an hourly analysis was detailed enough for our purposes, so demand and generation were averaged. Then, as explained in section 4.3, the voltages for the whole network were averaged per phase and hour in order to present the data in an apprehensible way.

The second main obstacle was the lack of functionalities provided by the PF4T license. It was expected to have the Voltage Profile Optimization and Optimal Capacitor Placement tools in order to optimize our network, but they were not allowed. Furthermore, the PV and QV curve calculations were only allowed for balanced networks. These absences were limiting and the study had to be conducted accordingly.

Also, for the unbalanced network study, the reactive power flowing through each phase and branch was different, which made it impossible to inject the appropriate amount of reactive power in each node and phase. Even more, the PV modules could only be connected in three phase, which did nothing to reduce the problem. In order to perform a complete study of the network it was decided to modify it into a balanced configuration.

6. ECONOMIC STUDY

The type of studies like the one performed in chapter 5 are going to become increasingly necessary due to the technical difficulties explained in section 2.2, so it is important to determine their economic cost to the electricity distribution companies that wish to perform them on their networks.

In table 6.1 the costs of the study have been detailed. The computer model chosen has been a PC HP 290 G1 Tower, Pentium, 4GB, 500GB [26], as similar as possible to the one used for the present project. A price for the commercial license of Power Factory with full capabilities, unlike the thesis license, has been estimated [27], with the help of a currency converter [28]. The amortization period for these two items has been estimated of 5 years. The salaries for the Junior Engineer and Supervisor, student and tutor respectively in this thesis, have been estimated from typical industry values.

Tool	Quantity (unit)	Price per unit (€/unit)	Amortization (€)
Computer	1	422,29	3,47
DIgSILENT PF4C	1	4400,00	36,14
		Total	39,61
Human Resource	**Working hours (h)**	**Salary (€/h)**	**Cost (€)**
Junior Engineer	360,00	10	3600
Supervisor	15,00	100	1500
		Total	5100
		Total costs (€)	5139,61

Table 6.1. Estimated cost of study

In addition to the cost of the study itself, the company must take into account as well the cost of installing either of the options proposed. From several reports a comparison between the costs of capacitors and StatVars, the devices analyzed in chapter 5, has been extracted. It is evident that StatVars are more expensive than capacitors (table 6.2), and that larger devices have a lower relative cost (figure 6.1).

(€/kVAr)	Capital cost	Installed cost	Total cost
Capacitor	7,63	5,30	12,93
StatVar	27,55	25,43	52,98

Table 6.2. Comparative of capacitor and StatVar costs in average [7], [29], [30]

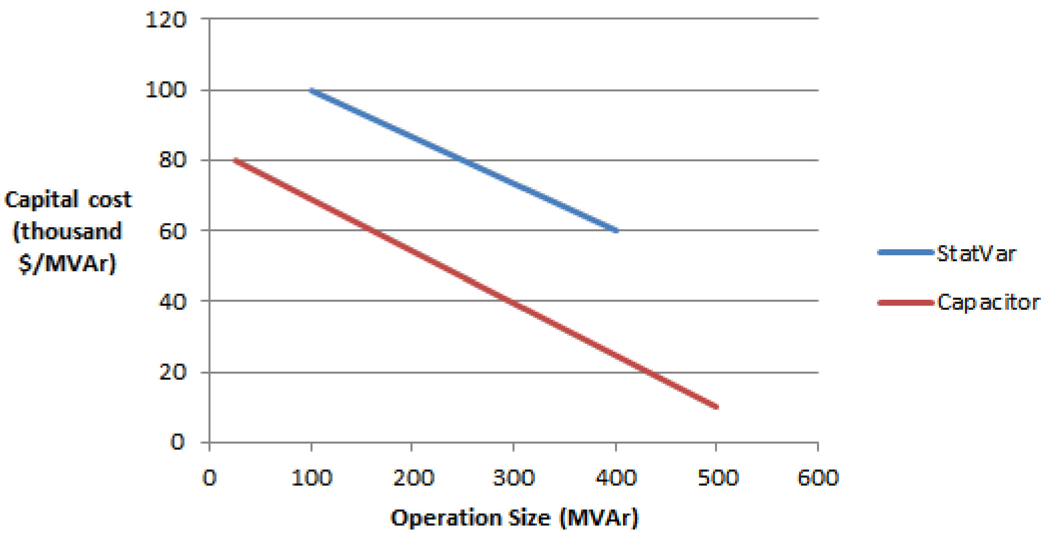

Figure 6.1. Inverse proportionality between size and unit cost [31]

The costs for a full project study and implementation of voltage control for an electricity distribution company on a radial, unbalanced network similar to the IEEE 34 would be as shown in table 6.3:

	Units	Size (kVAr)	Price (€/kVAr)	Devices cost (€)	Cost of study(€)	Total cost (€)
Capacitors	2	200	12,93	5.172,00	5139,61	10.311,61
StatVars			52,98	21.192,00		26.331,61

Table 6.3. Estimated invoice

The total cost if choosing StatVars would be more than 250% higher than if choosing capacitors. The study would account for barely a 20% of the total cost, while with capacitors it would be around 50%.

Before these data, perhaps the initial intention would be to choose larger capacitor banks to compensate reactive power at the minimum cost possible. However, from the analysis performed in chapter 5, we know that the best alternative to control voltage and reactive power from a technical point of view is placing several, smaller units of StatVars in strategic locations in the network.

Going for the cheap option and underinvesting in electrical infrastructure can lead to blackouts and cost far more than their prevention [32]. Power outages cause transport chaos, shutdown of critical infrastructures like hospitals and airports and huge losses for industry in all its levels.

Yamashita [33] proposes three approaches to compute the cost of such consequences:

$$MacroscopicCost = \frac{GDP}{TotalEnergyConsumption} \tag{6.1}$$

Macroscopically, research has found that regular outages in industry areas can have a significant impact on GDP, around 5%, which is a conservative estimate since it is difficult to account for small industry and household losses [34].

$$MicroscopicCost = f(Survey) \tag{6.2}$$

Through surveys it has been found that power outages pose a major challenge to economic growth in rural areas [35] and that most households would be willing to pay up to 40 € for a stable electricity supply [36], [37].

$$AnalyticalCost = OutageCost * \frac{ExpectedUnservedEnergy}{ActualUnservedEnergy} \tag{6.3}$$

This method allows a more precise insight on the costs for the parties involved. Insurer Allianz estimates such losses in $27 \cdot 10^3$ € for medium and large industry, and up to $15 \cdot 10^7$ € for telecommunication industries, far more reliant on electricity [38]. It estimates that, to meet the rising electricity demand for electricity by 2030, $11{,}5 \cdot 10^{12}$ € must be invested globally, half of that quantity on electrical transmission infrastructure rather than new generation [32].

To apply the cost of blackouts to our case, we must take into account that the impact of an outage on an electricity company is different to the rest of industries, and not very studied. Electricity companies must deal with repairs, insurance payment to customers and a reduction in their income due to unsupplied electricity [39]. The cost can be around 4.000€ per unsupplied MWh [40]. Knowing that the full load of the IEEE 34 feeder is 1,769 MW, a single 5 hour blackout, the average blackout duration worldwide [38], would cost the company 35.380€, more than double of the additional cost of installing StatVars respect capacitors.

In conclusion, it is profitable to invest in reliable infrastructure, StatVars in our case.

7. SOCIAL IMPACT

7.1. Change of paradigm

It is not possible to achieve an actually effective smart grid only from a technological approach. Smart grids do not only consist of advanced technology and smart power and voltage control. Smart meters help, but it is the people who have to make informed decisions about their energy consumption [41]. Thus, human perception about the smart grid affects its performance, but there is a tendency to neglect social aspects when developing and studying it [42].

Studies of social acceptance are particularly complex in this field, since electrical energy consumers regularly diverge from rational decision making. This is a market failure due to a lack of information. There is willingness in a majority of consumers to participate in the smart grid, but they lack information on basic concepts of quality of supply and load adjustment, so they approach this change conservatively [41].

Institutional factors have proved to be determinant in matters of acceptance [43]. Current institutions are not suited for renewables and smart grids, since these are best governed multi-centrally, both technically and socially. When control is handed to the users it will be a revolution. As they will be in charge and own their grid, they will be better able to participate in it [42]. Not only that, but they will be aware of the wider consequences of their actions and work together towards managing the common pool resources that are the electrical grid and the global climate [41], [42].

This consumer empowerment will necessarily lead to a change in the business model of traditional, centralized electricity firms. Keeping a good power quality and service is now more important than ever, as customer satisfaction and loyalty are growing in interest. If the power quality is bad, the brand name of the company may be damaged [44].

It is uncertain whether the change will be positive or negative for the firms, but undoubtedly the smart grids will and are causing a disruption in the sector. Smart grids are disruptive because they enable unprecedented behaviours: environmental friendliness, energy saving and control, bargaining power on the consumer's side, electric vehicle usage, higher quality supply demand, etc [43]. This threatens to decrease the traditional firms' efficiency and revenues, but they still fail to adapt [43], [45].

This is not particularly surprising. Barriers to innovation are particularly exacerbated in the case of sustainable technologies, as it is hard for businesses to cope with all the changes they encompass:

- The value will no longer be electricity, but efficiency and big data [43].
- This in turn will require close relations with ICT companies and marketing based

on information and advice rather than persuasion [45].

- The costs structure will completely change, adding the expense of communication facilities and removing those of peak generation, and, with decentralization, the operation strategy will be much more flexible [43].
- On top of all, it is hard to see the benefits when they do not come in the short term, or explain them to their customers [43], [45].

Moreover, besides all of these barriers, electricity companies need to deal with all the technical difficulties the smart grid brings with it: increased harmonics levels, which in turn cause overheating and early aging, transients, voltage sags and swells, etc [44].

7.2. Sustainable development

As it was commented in section 1.1, a reliable electrical access is key to a sustainable and equitable society, and its lack one of the main indicators of poverty [46]. In countries where there is lack of electrification and an uncertain supply, the population is forced to resort to other, much unhealthier energy sources like firewood [47] and prevents them from accessing basic elements for development like night lighting to extend the schoolday or internet access for information.

Energy poverty happens too in mostly electrified countries, although it takes a different form: there is no shortage of supply, but the electrical firms have the right to cut it if the bills are not payed. This only worsens the users in a situation of vulnerability, like the unemployed. Also, the inability to keep adequate temperatures in the household during winter is an actual health hazard [48].

The change of paradigm described in section 7.1 could completely turn the tables in this situation. Both in developed and developing countries a reliable electricity supply that the consumers could manage and be a part of would boost economy and employment, literacy, health and the state of welfare overall.

Furthermore, since one of the main points of the smart grid is to be able to enlarge the share of renewable energies in the electrical mix, all these aspects would be enhanced as well by the reduction in greenhouse gas emissions. Climate change would be mitigated, and all its larger consequences as well, such as floods, droughts, wildfires, ocean acidification, etc, that make life for humans and the rest of nature alike much more precarious.

7.3. ICT vulnerability

However, a there is a threat that is still very underdiscussed: how vulnerable the use of ICT (Information and Communication Technologies) makes the grid. Until now, energy security was mainly understood as reliable supply. However, the transition to smart grid poses an entirely different problem.

The increasing dependence on ICT in all aspects of society has been causing severe problems to the administrations of European countries in the form of cyber-attacks. Particularly notable was the three week assault on Estonia's government in 2007, one of the most internet dependent countries in the EU. This gets extremely worrisome when observed in the perspective of the international outage of 2006 that originated in Germany and extended to most of Europe and even Morocco through Spain [49].

It is feared that this vulnerability makes the electric grid a terrorist objective, both in itself or as a means to enter the communication infrastructure. This will open the gates for forced blackouts and sensitive information exposure. Protection measures include a greater number of intelligence devices and interconnections, so that there are more paths of flow and access, and controlling both physical and wireless accesses [49].

8. CONCLUSIONS

The "smart grid" concept has been a topic of discussion for some years now, but it seems that its true meaning escapes most people and the words end up being used as a blanket term for everything that sounds like a novelty in the electricity grid, without actual understanding.

The smart grid is an upgrade of the existing electrical grid and a change of mentality that will revolutionize a broad range of fields: engineering, ICT, environment, the electrical market, politics and societies around the world.

Technologically speaking, it is a highly interconnected and distributed grid (figure 8.1). It is able to isolate and resolve faults in a very short time, integrate renewable energies and keep stable voltage magnitude and frequency, among other things. To do this, it requires of implication from all consumers to manage their demand, install distributed generation, etc. This social dimension is the one that will affect the most the current paradigm of the electric sector: the market, companies and regulations will need to adapt to this new behaviour.

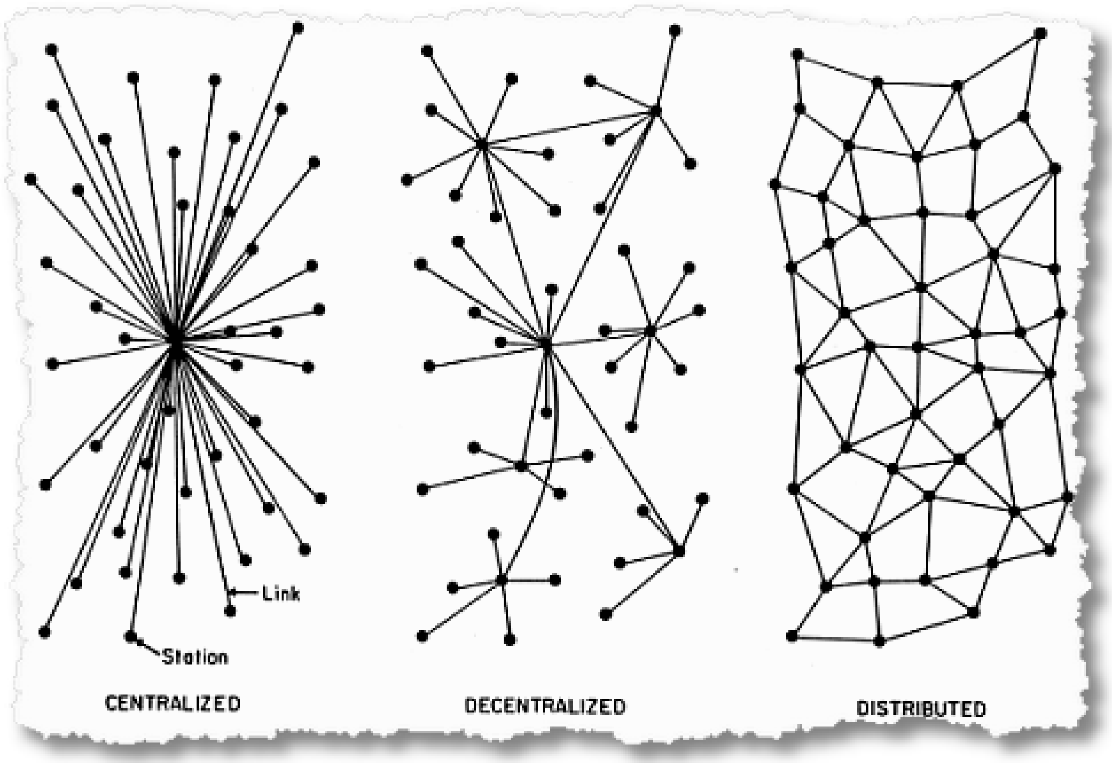

Figure 8.1. Conceptual transition of the grid [50]

So, why, if it comprises so much difficulty, money and change, is the smart grid central in today's dialogue for the future? Because its benefits, as abstract and imprecise as they might be, widely outweigh these inconvenients.

The path would be open for renewable energies and electric vehicles to be integrated, not only in large scale energy plants, but also as distributed generation, as there would be devices and mechanisms to control the imbalances they may cause. Greenhouse gas emissions would then be greatly reduced from both electricity generation and transport, two of the greatest emissions sources. Health would improve and climate change and its effects would be mitigated.

Both the improvement in health and climate disaster reduction, and a stable supply of electricity would greatly boost the development of the so called "third world countries". Electricity is crucial to most aspects of modern society: work, education, transport, etc, and the population values it as such.

With social participation to enhance these benefits, the electricity market would be transformed into a much fair and competitive one.

However, the smart grid is not without its drawbacks.

Voltage control and reactive power compensation have been one of the main concerns of the electrical grid, all the more for the smart grid. The absence of proper control causes fluctuations in the magnitude which can develop into faults and blackouts, costing large amounts of money and provoking chaos.

The present report has focused on the best way to deal with the increasingly complex task of voltage control, and two main conclusions have been extracted. One, it is more efficient to invest in dynamic control devices, like StatVars, both technically and economically. The other, networks must strive towards loop or interconnected topologies in order to avoid nodes having just one electricity source and therefore being much more vulnerable to tripping.

To help with voltage control are the ICT, implemented in the electric grid by means of smart meters and other monitoring devices. The enormous amount of data retrieved this way must be managed with modern algorithms that learn and adapt to every situation, and protected from cyber attacks, as the grid is a vulnerable point and private consumption information could do incredible harm in the wrong hands.

There are three key ways in which these challenges can be overcome: favourable regulation for new energy models, investment in transmission and communication infrastructure and, perhaps the most important of all, the spread of information, so the people who will benefit from it can participate, be invested and make the smart grid a reality.

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ANNEX A - IEEE 34 DATA

Node A	Node B	Length (ft.)	Config.
800	802	2580	300
802	806	1730	300
806	808	32230	300
808	810	5804	303
808	812	37500	300
812	814	29730	300
814	850	10	301
816	818	1710	302
816	824	10210	301
818	820	48150	302
820	822	13740	302
824	826	3030	303
824	828	840	301
828	830	20440	301
830	854	520	301
832	858	4900	301
832	888	0	XFM-1
834	860	2020	301
834	842	280	301
836	840	860	301
836	862	280	301
842	844	1350	301
844	846	3640	301
846	848	530	301
850	816	310	301
852	832	10	301
854	856	23330	303
854	852	36830	301
858	864	1620	302
858	834	5830	301
860	836	2680	301
862	838	4860	304
888	890	10560	300

Table 8.1. Line Segment Data

Config.	Phasing	Phase ACSR	Neutral ACSR	Spacing ID
300	B A C N	1/0	1/0	500
301	B A C N	#2 6/1	#2 6/1	500
302	A N	#4 6/1	#4 6/1	510
303	B N	#4 6/1	#4 6/1	510
304	B N	#2 6/1	#2 6/1	510

Table 8.2. Line Configuration Data

300	a	b	c	
R (Ω/mile)	1,3368	0,2101	0,213	a
		1,3238	0,2066	b
			1,3294	c
X (Ω/mile)	1,3343	0,5779	0,5015	a
		1,3569	0,4591	b
			1,3471	c
B (μS/mile)	5,335	-1,5313	-0,9943	a
		5,0979	-0,6212	b
			4,888	c

Table 8.3. Line Configuration 300

301	a	b	c	
R (Ω/mile)	1,93	0,2327	0,2359	a
		1,9157	0,2288	b
			1,9219	c
X (Ω/mile)	1,4115	0,6442	0,5691	a
		1,4281	0,5238	b
			1,4209	c
B (μS/mile)	5,1207	-1,4364	-0,9402	a
		4,9055	-0,5951	b
			4,7154	c

Table 8.4. Line Configuration 301

302	a	b	c	
R (Ω/mile)	2,7995			a b c
X (Ω/mile)	1,4855			a b c
B (μS/mile)	4,2251			a b c

Table 8.5. Line Configuration 302

303	a	b	c	
R (Ω/mile)		2,7995		a b c
X (Ω/mile)		1,4855		a b c
B (μS/mile)		4,2251		a b c

Table 8.6. Line Configuration 303

304	a	b	c	
R (Ω/mile)		1,9217		a b c
X (Ω/mile)		1,4212		a b c
B (μS/mile)		4,3637		a b c

Table 8.7. Line Configuration 304

Conductor	Type	Res. Ohms/mile	Res. Ohm/km	Dia. Inch	Dia. m	GMR Ft.	GMR m	Rating Amps
#1/0	ACSR	1,12	0,69593747	0,398	0,0101092	0,00446	0,00135941	230
#2	ACSR	1,69	1,05011992	0,316	0,0080264	0,00418	0,00127406	180
#4	ACSR	2,55	1,58450048	0,257	0,0065278	0,00452	0,0013777	140

Table 8.8. Line Conductor Data

Regulator ID:	1	2
Line Segment:	814 - 850	852 - 832
Location:	814	852
Phases:	A - B -C	A - B -C
Connection:	3-Ph,LG	3-Ph,LG
Monitoring Phase:	A-B-C	A-B-C
Bandwidth:	2.0 volts	2.0 volts
PT Ratio:	120	120
Primary CT Rating:	100	100
Compensator Settings (per phase):		
R - Setting:	2,7	2,5
X - Setting:	1,6	1,5
Volltage Level:	122	124

Table 8.9. Regulator Data

Node	Load Model	Ph-A kW	Ph-A kVAr	Ph-B kW	Ph-B kVAr	Ph-C kW	Ph-C kVAr
860	Y-PQ	20	16	20	16	20	16
840	Y-I	9	7	9	7	9	7
844	Y-Z	135	105	135	105	135	105
848	D-PQ	20	16	20	16	20	16
890	D-I	150	75	150	75	150	75
830	D-Z	10	5	10	5	25	10
Total		344	224	344	224	359	229

Table 8.10. Spot Loads Data

Node A	Node B	Load Model	Ph-A kW	Ph-A kVAr	Ph-B kW	Ph-B kVAr	Ph-C kW	Ph-C kVAr
802	806	Y-PQ	0	0	30	15	25	14
808	810	Y-I	0	0	16	8	0	0
818	820	Y-Z	34	17	0	0	0	0
820	822	Y-PQ	135	70	0	0	0	0
816	824	D-I	0	0	5	2	0	0
824	826	Y-I	0	0	40	20	0	0
824	828	Y-PQ	0	0	0	0	4	2
828	830	Y-PQ	7	3	0	0	0	0
854	856	Y-PQ	0	0	4	2	0	0
832	858	D-Z	7	3	2	1	6	3
858	864	Y-PQ	2	1	0	0	0	0
858	834	D-PQ	4	2	15	8	13	7
834	860	D-Z	16	8	20	10	110	55
860	836	D-PQ	30	15	10	6	42	22
836	840	D-I	18	9	22	11	0	0
862	838	Y-PQ	0	0	28	14	0	0
842	844	Y-PQ	9	5	0	0	0	0
844	846	Y-PQ	0	0	25	12	20	11
846	848	Y-PQ	0	0	23	11	0	0
Total			262	133	240	120	220	114

Table 8.11. Distributed Loads Data

	kVA	kV-high	kV-low	R - %	X - %
Substation:	2500	69 - D	24.9 -Gr. W	1	8
XFM -1	500	24.9 - Gr.W	4.16 - Gr. W	1,9	4,08

Table 8.12. Transformer Data

Node	Ph-A kVAr	Ph-B kVAr	Ph-C kVAr
844	100	100	100
848	150	150	150
Total	250	250	250

Table 8.13. Shunt Capacitors Data